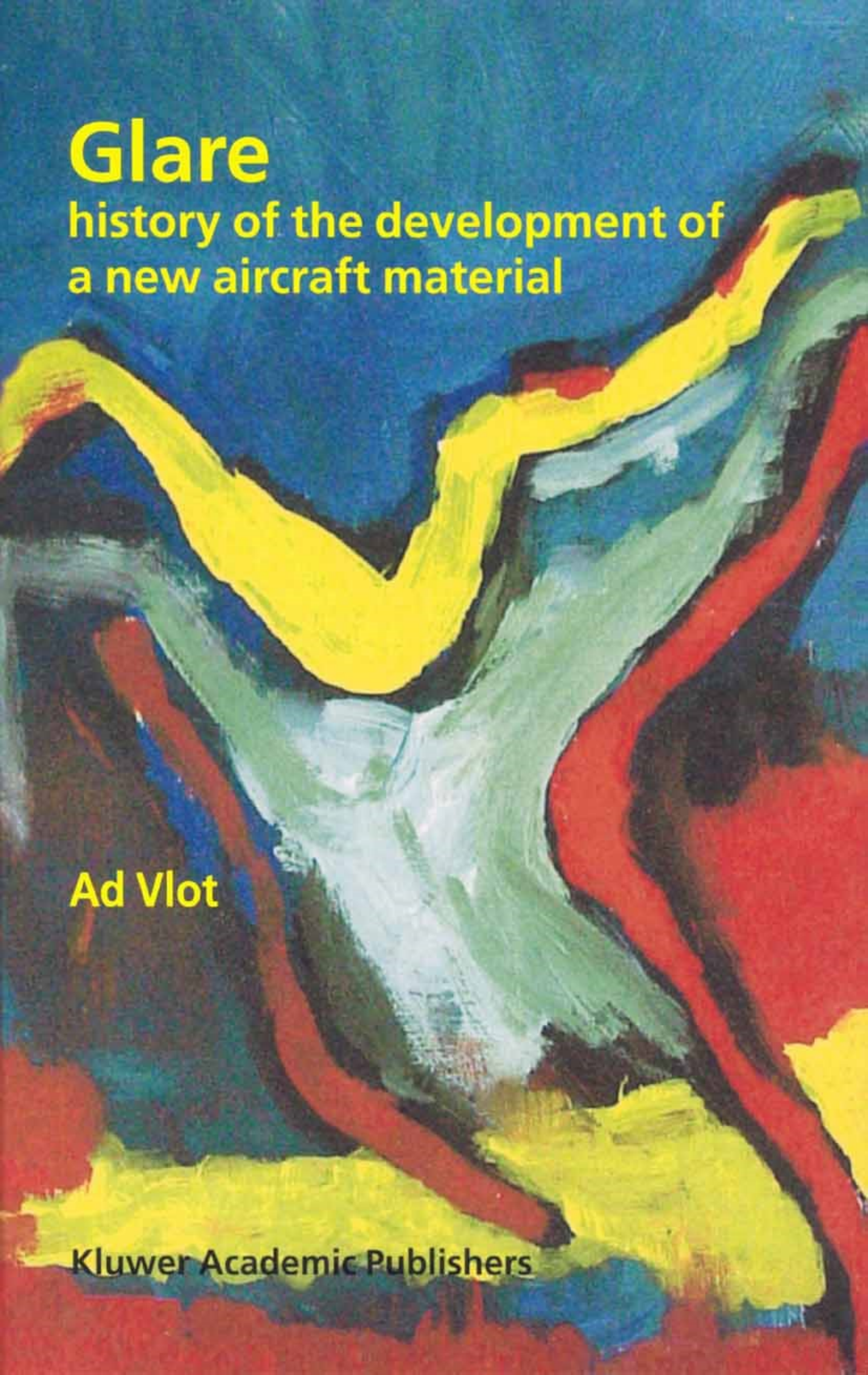

Glare

history of the development of a new aircraft material

Ad Vlot

Kluwer Academic Publishers

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by

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KLUWER ACADEMIC PUBLISHERS
NEW YORK, BOSTON, DORDRECHT, LONDON, MOSCOW

eBook ISBN: 0-306-48398-X
Print ISBN: 1-4020-0124-X

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Preface

Delft has long been famous for its pottery. However, Delft has recently also become widely known for producing another important material named 'Glare'. This is an aircraft material built up from thin layers of aluminium bonded together with adhesive containing embedded fibres. The resulting laminated material is designed to have a very high resistance against fatigue. The development and application of a new material for use in the primary structures of commercial aircraft is virtually a once-in-a-lifetime event. At the beginning of the 21st century, this is only the third time that a new class of materials has been applied in the primary structure of a passenger aircraft, with the two previous occasions being the change from wood to aluminium in the 1930s and the gradual introduction of composites (fibre-reinforced plastics) in the 1970s and 1980s. This book tells the story of the twenty years that it took to develop and promote this new material in a laboratory of a technical university. This is the right time to document the history of the development of Glare, as in a couple of years the memories of the key personnel involved will fade and the story could never be

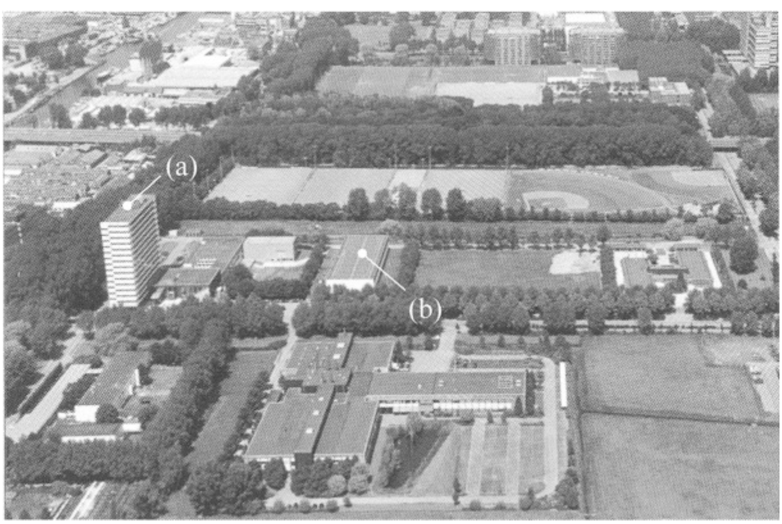
reconstructed in the same way using only the paper records preserved in the archives of Delft, AKZO, ALCOA and the other companies that played a role. In this book I hope to provide the inside story of this project, giving a taste of the unique style that characterised the work in and around our university lab.

This book is not meant as a success story to show the world how excellent our research group was, but as an inside story to give the reader an accurate picture of the process and the people, the frustrations and the successes, and the stamina, belief and dedication that is required to enable such a new technology to take off. This book has a number of themes: the importance of the culture of an organisation, the tension between fundamental and ‘applied’ research, the co-operation between the university and industry, a new technology as a plaything in and between companies, the importance of belief. I believe that telling such a story is useful, since public attention is usually drawn only to the results of new technology, for example a shiny aircraft or a dark disaster. What happens behind the scenes is not the unworldly work of researchers with thick glasses who wear white coats and stare all day through microscopes, expressing their views in mathematical formulae. It is the work of normal people. It is not dull work compared, for example, to the work of surgeons and lawyers played in many television soaps, but fascinating work aimed at understanding and changing our world; work carried out by a team of enthusiastic people that share not only their work but also their lives.

The main scene of the story is the Structures and Materials Laboratory of the Faculty of Aerospace Engineering of the Delft University of Technology in the Netherlands. In this laboratory, there are always several projects in progress at the same time. This book focuses on the development of two fibre-metal laminates, Arall (with aramid fibres) and Glare (with glass fibres). The enthusiastic driving force behind this work was Professor Boud Vogelesang, and this book is therefore dedicated to him on the occasion of his formal retirement, which was marked by an international conference on fibre-metal laminates in Delft from the 24th to the 26th of September 2001. The work of another group of people in this laboratory, led by Professors De Jong and Beukers, is not treated here, but it has to be said that their work was also essential for the development of fibre-metal laminates. As is usual at the Delft Structures and Materials Laboratory, both teams worked together within the faculty research group, although the relationship was at times fuelled by competition and fierce discussions. However, the complete story of the Structures and Materials Laboratory in

Delft would take a separate volume. More about the work of Beukers can be found in the book *Lightness.*[1]

This book can never be complete. The development of the new material took place as a result of the interactions of many organisations and people. Over the lifetime of the project, more than one hundred undergraduate and graduate students wrote their Master's theses on related problems, each making a small contribution to the jigsaw puzzle. Decisions were taken and battles were fought behind the doors of conference rooms and boardrooms of different companies in Europe and in the U.S. To mention everyone's individual contribution would take us far beyond the scope of this book, which focuses on the core developments. To readers who find that their contribution is not mentioned here, I can only say I am sorry. Exclusions were inevitable; they certainly do not imply that the omitted work was irrelevant. Even within the present text choices had to be made. It may be that this has led to occasional oversights and mistakes. I count on your consideration. To prevent mistakes, the only alternative is to not write a book like this and I think that would be a bigger mistake.



Aerial view of the Faculty of Aerospace Engineering of the Delft University of Technology in the Netherlands: (a) main building, (b) Structures and Materials Laboratory.

[1] Adriaan Beukers and Ed van Hinte, *Lightness – the inevitable renaissance of minimum energy structures.* Rotterdam: 010 publishers, 1998.

This book is based on the personal archives of Boud Vogelesang and myself and on interviews with all the key personnel involved:

Roel Marissen (27 January, 2000)
Jaap Schijve (14 March, 2000)
Geert Roebroeks (12 September, 2000)
Buwe van Wimersma Greijdanus (21 February, 2001)
Marc Verbruggen (26 February, 2001)
Thomas Beumler (21 March, 2001)
Jan Willem Gunnink (27 March, 2001; 11 April, 2001)
Bill Evancho (4 April, 2001)
Boud Vogelesang (23 April, 2001)
Daan Krook (23 April, 2001)
Bob Bucci (25 April, 2001)
Adrie Kwakernaak (12 June, 2001)
Jens Hinrichsen (13 June, 2001)

Most of these interviews, which were conducted on the dates shown, were recorded on tape. In some cases reports had been written, and the information they contain was included in the various chapters. In most cases a key person played a main role in one of the episodes of the story and I was able to focus on this person in the associated chapter of the book. These chapters were checked by these relevant key persons, and I would like to thank all those involved for their time and the trust they placed in me.

This book was written from the specific perspective of the author. I earned my MSc and PhD in the lab in Delft. For a large part of the story I was involved as a researcher in the lab, where I am still working. I hope to pass to you the joy of working in this laboratory environment. Being involved in these events myself means that my point of view cannot be objective – if such an ideal, objective standpoint exists. However, being involved also has big advantages when a story has to be told. I have tried to be honest. This was not always easy, because not all that happened with Glare was sweetness and light. As Jens Hinrichsen said in his interview: “We live in an imperfect world.” Describing this imperfect world can require careful handling to give the right picture without hurting or damaging people and organisations. Although the book describes the struggles and, sometimes, frustrations that are common when people work closely together, the text was not meant to offend people or organisations. Irritations were also

uncalled for, since the relationships described here were never really broken and people always remained on speaking terms.

I especially want to thank Marc Dierikx, *the* Dutch historian on aviation who helped me to change my English sentences into a real text. It was always a joy to see how a miracle took place and a 'crippled' piece of text could really 'run' smoothly. It was really an example of good co-operation between the arts and the sciences. I also want to thank Jan Szechi, who did the final check on the English grammar. Students Ronald van der Meijs, Lex Dop, Geoff Morris and Dort Daandels did a very good job by taking care of the layout of the book. Frans Oostrum took care of many illustrations. This was not easy because through the years many photographs were taken of specimens and structures but not of the people who tested them, and the people are the focus of this book. Willemien Veldhoven and Frans Oostrum worked together on the cover of the book, which is based on a design of former student Wendell Lynch. It shows an artistic impression of a hummingbird, the 'high-tech' bird chosen by Boud Vogelesang as the logo of the lab. It is meant to keep engineers modest, since we have a hard time using clumsy technology to compete with the elegance of nature.

This book would never have been *started* without the help of Erik Tempelman. We planned it as a co-production, but because of a form of RSI we were not able to execute what we planned. However, he played an essential role during the conception of the book and wrote a large part of the prologue. And this book would never have been *finished* without the support of Jan Willem Gunnink. When I was halfway and wanted to give up, he urged me to continue. Here it is.

Ad Vlot
Delft, July 2001

Prologue

On the 10^{th} of January 1954, the seemingly impossible happened – and barely three months later it happened again. A fully loaded Comet jet airliner crashed. Both went down in the Mediterranean, the first close to Elba, taking its crew of six and 29 passengers with it, and the second into the sea south-east of Naples, killing 21 people. The world was in shock. The Comet, heralded in 1949 as the vanguard of a new era of high-speed air travel, was the pride of the British aircraft industry.

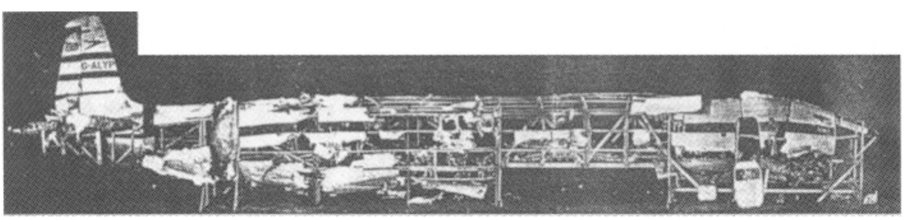
It demonstrated Britain's technological lead over the Americans in the development of jet engines. De Havilland, the manufacturer of the aircraft, never quite recovered. The American aircraft industry, Boeing, Lockheed and McDonnell Douglas, took the lead and kept it until the hegemony of the U.S. in aviation was finally balanced again by the European consortium Airbus Industrie towards the end of the century. Months of painstaking investigations followed the Comet crashes, going so far as dredging up the wreckage of the first aircraft from its uneasy grave at the bottom of the sea and reconstructing the Comet from the debris.

First commercial jet airline service on the 2nd of May 1952: departure of the De Havilland Comet G-ALYP.

Finally, the cause of the accidents was established: metal fatigue. Fatigue cracks occurred at the edges of square openings in the fuselage skin of the aircraft. The Comet accidents put fatigue in the spotlight as a major design requirement for aircraft structures. We will see in the first chapter that De Havilland was the first producer to encounter fatigue in this dramatic way, and that the company was also the birthplace of metal bonding technology and therefore ultimately also of Glare, the material which was especially designed to solve the fatigue problem.

In hindsight, the irony is inescapable. For centuries, comets had been the symbols of doom. Of course, this was not the reason why De Havilland chose that particular name for their most advanced product, aiming instead for the other well-known property of comets: their speed. The Comet was indeed exceptionally fast for its time and was the first passenger aircraft to be equipped with jet engines. The engines, one of the technical legacies of the Second World War, made the Comet unique, but were also the cause of the aircraft's downfall. To work efficiently, high-speed jet aircraft have to cruise at much higher altitudes than their slower, propeller-driven counterparts. The Comet took its passengers to heights previously only reached by experimental planes. To keep those passengers comfortable at

such heights, the aircraft's cabin had to be pressurised like a balloon. In itself this was nothing new – propeller aircraft like the Lockheed Constellation were also pressurised – but at the extreme altitudes at which the Comet operated, the stresses in the skin of the fuselage resulting from internal pressurisation were much higher. The cabin had to be pressurised for every flight, both during the climb to cruising altitude and while cruising, after which the pressure is released during descent. This means that the stresses experienced in the skin of the fuselage have a cyclical character; the material of the skin is stretched and released again, and again, and again. This cyclical loading leads to what we call 'fatigue'. Once a fatigue crack occurs, it will increase by a small increment during every cycle until a critical crack length is reached, at which point the fuselage tears open and explodes like a punctured balloon. Cracks start to form at locations under high stress; in the Comet, cracks initiated around the rivet holes close to the edge of windows in the fuselage skin. The explosive decompression led to instant loss of control and a tragic crash. The first Comet's experimental Cockpit Voice Recorder – a device already in regular use at that time – revealed that the explosion had actually silenced the pilots in mid-sentence.



Reconstruction of fuselage and tail unit wreckage of G-ALYP, the first crashed Comet.

It is often thought that metal fatigue was unknown to the Comet's designers. This is not true. They did know about it, and in fact tested the aircraft's fuselage to see if it had sufficient resistance against fatigue. However, their understanding of this phenomenon at the time was still limited and therefore they performed the wrong test. First they applied twice the internal pressure difference to the fuselage than that experienced in actual flight. After this high static load the fuselage was tested by cyclically putting the fuselage under pressure. Approximately 20,000 cycles were put on the fuselage, corresponding to the same number of flights. We now know that applying a high static load *before* the fatigue test will have a favourable

effect on the metal's fatigue life. At high stresses the metal deforms permanently (plastically) in places experiencing high levels of stress, for instance around rivet holes. Therefore the surrounding material, which stays elastic, will induce a compressive stress on the elongated material, effectively closing any cracks that may occur due to fatigue. As a result, the test on the Comet fuselage greatly overestimated the structure's life. The two Comets went down after completing barely one thousand flights.

Although all materials may suffer from fatigue, fatigue is especially critical for metals under high cyclical loads and fatigue became a problem in structures after the Industrial Revolution. Whöler first discovered this in the axles of railway carriages at the end of the 19th century. Metal passenger aircraft first appeared during the early 1920s, with German designs from Rohrbach and Junkers. However, Boeing and Douglas were the first aircraft manufacturers to create worldwide success stories with the truly modern all-metal Boeing 247, and the Douglas DC-2 and DC-3 in the 1930s. The DC-3 Dakota or Gooney Bird – one of the rare aircraft getting not one but two nicknames – has become a symbol of unparalleled reliability. Some are still in regular use even today.

To most people, this success would seem only natural: after all, is not metal simply better and more reliable than wood? But what few people know is the fact that the runway of the all-metal aircraft was paved with problems. Early metal aircraft had shown themselves to be prone to persistent corrosion, surprisingly vulnerable to fire, laughably poor in performance in terms of payload, and – last but not least – so expensive as to deter even the military. Initially metal failed to live up to its promise so completely that it is remarkable that these problems were confronted at all. Driven by their unshakeable belief in metal, which seemed to be so much more 'scientific' and reliable than wood, the industry finally solved the problems and came up with the DC-3. A critical assessment of the all-metal aeroplane's early history from an engineering point of view reveals that it is the Dakota's success that is surprising, not the Comet crashes. Clearly the introduction of a new material must be accompanied by significant belief to overcome all the difficulties that initially make the new material inferior to existing technology. The success of a new technology that has to replace an existing one is therefore probably never instantaneous but the eventual outcome of 'blind' variation.

The immediate problem of metal fatigue in the pressurised fuselage structure was also eventually solved. Although the unfortunate Comet itself

became a victim, the aircraft's successors in the U.S. proved to be both safe and reliable. The Comet accident stimulated enormous research efforts aimed at understanding and avoiding fatigue cracking. Today, the all-metal jet aircraft is the rule in air transport and it has become the safest means of transportation. This does not mean that fatigue is no longer an issue; in fact, quite the opposite is true. Most primary parts still have to be designed with fatigue as a critical factor. In service, fatigue cracks cannot be prevented and their growth cannot be completely eliminated. Special components called 'crack stoppers' and fail-safe structures with multiple load paths are applied to prevent the sudden, unstable crack growth that took place in the two Comets. Since the end of the 1970s aircraft structures have been designed to be 'damage tolerant', which means that safety is assured by using structures that can tolerate significant damage, and by frequent inspections that prevent the occurrence of more damage than each part can bear. Without fatigue, aircraft could be significantly lighter and hence have a better performance. The aircraft would also be significantly safer. They would need less maintenance and the dream of any aircraft manufacturer, and operator, is a 'carefree' structure. Today's aircraft have been derisively, but correctly, described as a 'flying collection of cracks'. The cracks are small and safety depends on regular and carefully executed inspections, after which any cracks that are found have to be repaired. Even with proper maintenance, an occasional incident or even an accident – the difference is literally a matter of life and death – still occurs, especially with so-called 'ageing aircraft'. The world's fleet of commercial aircraft is ageing because the aircraft are being used longer for economic reasons and they approach or even exceed the anticipated life span for which they were designed and tested. With frequent inspections and repairs, fatigue cracking can be controlled in these aircraft. It can also go wrong. An infamous example is the accident in 1988 in which a Boeing 737 of Aloha Airlines lost one-third of its upper fuselage, killing one flight attendant who was sucked through the hole created. During its life span of almost 100,000 flights, this aircraft had accumulated fatigue cracks at many rivets in the fuselage lap-joints, which finally caused the fuselage to tear open like a broken zip.

Such 'multiple site damage' is especially dangerous because the cracks themselves are not long enough to be critical, but in combination the interaction of the cracks may lead to failure. Since the Aloha accident, large cracks have occasionally been found in other aircraft fuselages, but

fortunately this has not led to accidents. For obvious reasons, these findings have not been disclosed to the public.

Fatigue may be especially critical in combination with corrosion. Corrosion damage is the most frequent type of damage occurring in aircraft structures, leading to a significant maintenance burden for the airlines. Especially at rivet holes, the locations that are also critical in fatigue, a combination of moisture ingress and fretting due to sheet materials sliding over each other can lead to severe corrosion damage. Fatigue crack initiation can be the result of this. Obviously there is a need for a fatigue and corrosion resistant material to improve performance because the aircraft can then be designed to be lighter, with lower maintenance costs and a higher level of safety.

The Aloha accident showed the importance of fatigue for ageing aircraft and of proper inspection and maintenance.

During the 1950s and 1960s a new class of materials emerged: fibre-reinforced plastics (composites). Modern fibres such as carbon, aramid, glass and boron fibre, are the stiffest and strongest materials known. However, since you cannot build a structure from fibres in most cases, they have to be embedded in another material, usually a plastic. Fibres have to be aligned in the same directions as the loads in the structure. The plastic matrix, along with the requirement that fibres run in different directions, increases the weight of composites while decreasing strength and stiffness

in terms of stress (= load per unit area). Even so, very high stress levels and significant weight savings can be reached compared to metals. The English scientist Norman de Bruijne was the first to propose composite materials for aircraft structures. Apart from their high specific strength and stiffness, these materials can be easily moulded and complex shapes and smooth surfaces can be produced. Moreover, composites hardly suffer from fatigue and do not suffer from corrosion, although degradation may occur due to environmental influences such as moisture. In particular, the composites with carbon fibres that became available in the 1960s were expected to be widely used in aircraft. Fibre-reinforced plastics are frequently used in the bodywork of cars and for small boats, but their application in aircraft structures has so far remained limited.

Thirty years later, around 80% of a civil aircraft is still made from aluminium, and composites still face their bright future. They continue to be referred to as ‘advanced materials’ despite their age. Applications in primary structures are mainly limited to military aircraft, helicopters and an occasional business jet. In civil aircraft the main load carrying parts, i.e. the fuselage and the wings, are made of aluminium alloys. Composites are used for tailplanes, covers, flaps, and fairings. A breakthrough for composites in the wing may be the carbon composite centre section of the wing in the Airbus A380. In other locations, such as the engine cowlings, composites have been replaced by metal structures because the brittle composites are more susceptible to impact damage, which leads to high maintenance costs. During their normal service life, aircraft structures are chipped, hit and scratched countless times. Metals undergo plastic deformation through the creation of dents, while composites tend to break and undergo delamination of the various internal layers of the material. Another problem afflicting composites is the huge gap between scientific modelling and engineering design tools. As a material, a composite is highly complex and to predict its damage resistance is extremely complicated. Computer models are used for this, but their accuracy leaves much room for improvement. Although metals may be prone to fatigue damage, the prediction of fatigue initiation and growth is relatively simple in a design process. As a result, it is more difficult to optimise a composite structure. The assumptions that are made with regard to the possible weight savings from the use of composites are often conservative. For a long time, composite structures have also been expensive. To the military this has always been less of a problem, and this is why composites are enthusiastically applied in fighters and bombers.

Another problem has been that composites require a fundamentally different approach towards manufacturing. Because industry never has an easy time abandoning old habits, making a change has required several decades.

This book tells the story of a third class of aerospace materials: fibre-metal laminates. The new material is a hybrid, built up from aluminium and fibre-reinforced plastic layers. I will show in the first chapter that the material can be regarded as having evolved from bonded metal structures. The question therefore arises whether fibre-metal laminates are modified aluminium alloys or a combination of metal and composites. This issue played a significant role at the end of this story within the development of the Airbus A380, due to a controversy between the German engineers of DASA and the French engineers of Aérospatiale. Within aircraft manufacturing companies, engineering groups focusing on aluminium have very different cultures and methods from those working with composites, and are in continuous competition with each other for the application of ‘their’ material.

In five chapters, the development of the fibre-metal laminates Arall and Glare is described. We start by looking at the development of bonded structures in the U.K. and the first combination of fibres and metals in the U.S. and at Fokker. The story then proceeds with the first tests on the optimised fibre-metal laminate, Arall, in Delft in 1978 and ends with the choice for another variant of fibre-metal laminates, Glare, for the Airbus A380 super-jumbo in 2001. As will be shown, the path of these laminates from concept through first tests to commercialisation has been long and full of surprises. The process was far from being a straightforward application of scientific and economic principles. Technology usually follows an erratic course of its own. Material selection is not a straightforward, purely objective process. It is not simply a matter of high strength and low weight; many material properties are involved, and the trade-off between them is highly complex. In part it depends on experience and fashion. Strength and density are just two of the many factors that play a role in aircraft design; others include damage tolerance, fatigue properties, strength in the presence of holes (blunt notch strength), durability, manufacturing aspects, inspectability, reparability, resistance to accidental impact damage, stiffness, behaviour in structures and joints, off-axis properties and so on and so forth. And of course the cost is also a crucial factor. Somewhere in the design process a choice is made, but since a fully detailed duplication of the design process, including aspects of production and service, is never done for two different

materials, a one to one comparison is usually impossible. The advantages and disadvantages of materials gradually evolve on the basis of experience.

The story behind the development of Glare shows that new technology comes into being as the result of considerable personal efforts by people who believe in the outcome. It is the work of humans, not the application of science. Human perseverance, creativity and genius make up the heart of invention. However, the long delay associated with the introduction of this new technology was not caused by the fact that developments in aircraft engineering take a lot of time because extreme care has to be taken to preserve safety. The inertia of the aerospace industry is not primarily a matter of safety issues. This story will show that it takes far too much time before a promising new technology gets the chance to prove itself. That Glare ever made its way into aircraft production was only possible because some people had faith in it, and because of the support of a university.

1

The birth of Arall (1945-1981)

The aircraft industry in the Netherlands

When the war ended in 1945, the German armed forces left the Netherlands a devastated country. Liberation brought many changes socially, politically, and economically, as the country had to adapt itself to post-war conditions. A prime concern was that the industrial infrastructure had to be rebuilt. Reconstruction required vast amounts of money, predominantly in hard currency as vital supplies had to be imported from the United States. The hard currency needed had to be earned from exports and for that reason the government embarked on a course of industrialisation. The Netherlands had taken the road towards modernisation and industrialisation comparatively late. The pre-war society was largely orientated towards agriculture, although industry had been growing in importance. Compared to surrounding countries such as England and Belgium, this was a fairly recent phenomenon. Starting slowly around 1850 and really gaining momentum from 1900 onwards, the country had

undergone a process of change from an agricultural, conservative nation. The government sought to break away from the strong tradition of international, seaborne trade that dated back to the Golden Age, when this tiny country tried to rule the waves. Some of the new industrial enterprises were even very successful, including the Fokker aircraft manufacturing company, which led the world market in aircraft manufacturing in the 1920s. Fokker's origins as an aircraft manufacturer lay in Germany, but after the First World War, Anthony Fokker, the energetic flying Dutchman, had transferred his activities to his home country. With tacit support from the German government, which sought to evade Allied measures aimed at dismantling the German military industrial complex, he had loaded his machines and equipment onto six trains and managed to transport them across the border. Fokker subsequently founded a new factory in Amsterdam in July 1919 and continued his aircraft manufacturing work, although for other customers.

The year 1919 was crucial for Dutch aeronautics. It marked the starting point of an enthusiasm and even passion for aviation in the Netherlands and her strong involvement in this field of technology up to the present day. That year the ELTA (*Eerste Luchtvaart Tentoonstelling Amsterdam*) aeronautical exhibition in Amsterdam attracted more than 500,000 visitors in six weeks. Fokker started his company in the ELTA buildings that were left empty after the show was over. The national carrier KLM and the Dutch Aeronautical Laboratory NLL (the present NLR) were both founded in that same year.

Although aviation has from its very inception been associated with state-of-the-art technology, 'industry' was not the right word to identify aircraft production in 1919. Hands-on experience was as crucial to Fokker as it had been to the Wright brothers. It is true that the Wright brothers had used and expanded the aeronautical sciences, for example by doing systematic tests in a wind tunnel. Nonetheless, they were primarily bicycle repairmen who built the wind tunnel they used, and later their aircraft, with their own hands. This combination of pragmatism, hands-on experience and scientific methodology, driven by the boundless passion for flight were the key factors in the Wright brothers' success in 1903. In the days when Fokker was working on the cutting edge of the new aviation industry, twenty years after the Wrights' first powered flight, craftsmanship was still a vital part of building aeroplanes. Aircraft design was not so much a matter of applied science but of feeling and of experience. However, know-how was expanding rapidly

since the time to design and build a new aircraft could normally be measured in months rather than years, which meant that feedback was quick. The most revolutionary part of Fokker's design concept – twenty years later than the Wright brothers – was that he combined a wing of bonded plywood with a fuselage that consisted of a truss of welded metal tube covered with fabric. By bonding the various layers of plywood, he could position the fibre orientation of the wood in the optimal directions for which strength was required. This avoided the problem that a sheet made from one single piece of wood would have its fibres running in only one direction and would therefore be weak and easily split in the other directions. In this way, Fokker managed to integrate the design features of several German aircraft designers of the First World War. In 1916, he combined Junkers' cantilever wing with the plywood veneer wing covering developed by the Swedish engineer Villehad Forssman. Fokker's company stuck to this successful concept, even when the American aircraft industry adopted aluminium on a large scale, although Fokker was canny enough to buy the rights to sell all-metal aluminium Douglas aircraft in Europe. In 1934, he introduced this aircraft in the Netherlands in conjunction with KLM. However, the battle between wood and aluminium was still an uncertain one in those days and the outcome was largely dependent on the direction that aviation would take. Fokker's passion for flying, his brilliant feel for the relationship between the flying characteristics of an aircraft and its design and his energetic and stubborn tradesmanship were clearly not balanced by the feeling and insights required to successfully lead an established company.[1]

The first experience of the Fokker company with the design and manufacture of aluminium structures was on military aircraft just before World War II. In the latter half of the 1930s, Anthony Fokker relinquished full control over the running of his company, making room for new approaches towards aircraft construction. An influx of new capital combined with increasing international tension to produce a steep rise in new designs and the production of aircraft. The Dutch designers even had an all-metal passenger aircraft on their drawing boards when the Germans overran the country in May 1940, seized the Fokker factory and forced it to work for their air force. During the war, Fokker manufactured components and did some design work for German military aircraft. However, the Fokker designers kept the all-metal passenger aircraft in their drawers and secretly continued to

[1] Marc Dierikx, *Dwarswind – een biografie van Anthony Fokker.* Den Haag: Sdu uitgevers, 1997.

work on it. In the course of the war, the various departments of the company were spread over the Netherlands for safety reasons, but this could not prevent heavy damage due to Allied bombing.

Although Fokker had been by far the largest Dutch aircraft producer before the war, it had not been the only one. The Netherlands had possessed several aircraft manufacturers in different parts of the country, of which the Rotterdam-based Koolhoven factory had been Fokker's biggest competitor. Of the others, Aviolanda, situated in Papendrecht close to Rotterdam, is worth mentioning. In Papendrecht, Aviolanda had been the first company to build all-metal aircraft in Holland. From the late 1920s the small company manufactured, under license, flying boats for the Dutch navy air service designed by the German manufacturer Dornier. For that reason, the company was not situated close to an airfield but built on a riverbank. After the war, Aviolanda became a part of the Fokker company; at the end of our story the Papendrecht site will play a role as the first location of a Glare manufacturing plant.

The origins of our story can be traced back to the devastated Fokker facilities of 1945, and actually even to the bonded plywood wing structure introduced by Anthony Fokker. The engineers that had to start to rebuild the company from scratch grasped the opportunity to introduce new technologies. Engineers love such situations. In the late 1940s, Holland started to rebuild its industrial facilities with Marshall Plan aid. Within this context the government appointed a special committee, chaired by Theo Tromp from the Philips company, to initiate a debate on the question of whether the aircraft industry should be rebuilt – and if so, then how. This was no easy matter, as it involved both construction technology and perceptions about the market for aircraft. With respect to the former, Fokker had already been struggling to keep up with international state-of-the-art technology in the 1930s. The problem had only become worse due to the rapid development of the aviation industries in the United States and the United Kingdom during the war, especially with regard to the industrial manufacturing of large quantities of aircraft. Aircraft manufacturing had changed profoundly in this way from craftsmanship to industry. Nevertheless, the Tromp Committee reported positively, based on arguments such as the availability of cheap labour in the Netherlands, the possible spin-offs from this high-tech industry to other industries and military necessity. The report echoed the spirit of enthusiasm created by the ELTA exhibition in 1919 and gave evidence that high hopes were still very much alive. As a result of the

report of the Tromp Committee, a special institute, the *Nederlands Instituut voor Vliegtuigbouw* (NIV) [Netherlands Institute for Aircraft Development], later renamed 'NIVR' to add the 'R' of *Ruimtevaart* [Space], was founded in 1947 to distribute government money and monitor research and development programmes. The committee also recommended that all three surviving aircraft companies – Fokker, Aviolanda, and the aircraft branch of the De Schelde shipyards – be combined into one company under the name of 'Fokker'. However, this major reshuffle of the industry proved difficult to achieve and after years of discussions, the envisaged merger foundered in 1949.

Metal bonding

Eager to claim a position in post-war international aircraft construction, in 1946 the Fokker company engaged in the development of small military training aircraft, based more or less on pre-war construction practices. These trainers, designated S-11 and S-12, were built at the company's own risk. These projects served as 'stepping stones' towards more complicated products such as the two-engine S-13 and the S-14 jet trainer. Qualified manpower was available to develop them, since just before the war, in 1940, an academic aeronautical engineering department was created at Delft University of Technology. Delft had always been a university for ship and bridge builders and civil engineers who created dikes, railroads and polders. Professor van der Maas, the driving force behind the aeronautical department was strongly rooted in this practical tradition. He was not only a professor in Delft, but also headed the NIV and the NIL and was therefore able to bring together those in education, research and manufacturing to work towards a common dream: the production of new aircraft by the Fokker company in order to keep the Dutch spirit of flying alive. Delft provided young, smart and very eager engineers to perform design and development work at Fokker and research at the Dutch Aeronautical Laboratory NLL. The knowledge gap that had to be bridged was therefore smaller than the industrial and commercial gap. Due to the openness of the international aeronautical research community, the technical capabilities of these engineers rose rapidly.

One of those eager young engineers and students of Van der Maas from Delft was a Dutchman with a German name: Rob Schliekelmann.[1] When asked, he remembered his starting date at Fokker exactly: the 23rd of August 1948. He would stay there for over forty years until his retirement. Before he started his career at Fokker, he had worked as a journalist, but his passion was building wooden model aircraft as a hobby. It was to obtain balsa wood and plywood for his hobby that he first established contact with the Fokker company. His presence in the company was not unnoticed. An assistant of Van der Maas went to Schliekelmann's mother with the message that they could use him for the company. He had already worked for KLM and had spent some time in England for the airline in 1946 as a trainee at the aircraft manufacturer De Havilland.

This British company had extensive experience with bonding. De Havilland was something of an exception in aircraft construction, being one of the last manufacturers to build aircraft that were predominantly made from wood. While most other companies had made the jump to metal construction in the 1930s and had consequently switched to riveting to join the metal parts, De Havilland had defiantly taken wood construction to its limits. During the war, De Havilland had built the famous Mosquito, a wooden fighter-bomber aircraft originally intended as a surrogate in case of aluminium shortages, but which actually turned out to be one of the best fighters and bombers of the war. The wings and fuselage of the Mosquito were built by laying up thin layers of wood with adhesive in a curved mould, in a manner similar to that used by Fokker for the wings of his successful aircraft of the 1920s. As we will see, this method also resembles the way the curved Glare fuselage panels for the Airbus A380 are produced at the end of our story.

Because of its alternative construction practices that relied so much on wood bonding, De Havilland became the first company that also bonded metal parts together. An adhesive suitable for metal was discovered at the beginning of the 1940s by a British researcher with a Dutch name, Norman de Bruijne, who worked on synthetic glues. De Bruijne was a dean at Cambridge University and worked with the famous scientist Rutherford. De Bruijne was also a good friend of Anthony Fokker and had previously worked on synthetic glues for the aircraft industry, developing a wood adhesive with the name 'Aerodux' that was used by De Havilland. Curiously, his hobby, like Schliekelmann's, was the building of wooden model aircraft, in the course of

[1] Interview transcription by Jan Anne Schelling, a former Delft student.

which he experimented with different mixtures of adhesives to improve bonding. To connect parts, pressure had to be applied to the wood in order to press the different layers together and to ensure a permanent fix. De Bruijne also used temperature, heating the metal press plates that applied the pressure. Two hot plates exerted pressure on the wooden parts and the adhesive in between, making the adhesive solidify and connecting both layers, a process that is called ‘curing’.

After one of his experiments, De Bruijne found that not only were the wooden parts of his aircraft model bonded together, but the adhesive had flowed in between the hot plates of the press and had effectively bonded the metal plates too. De Bruijne transformed this failed experiment into a successful one. Instead of cleaning the press and starting with a different adhesive, he realised that he had found something new and promising: metal bonding. De Bruijne used his contacts with De Havilland to introduce the new discovery into aircraft construction.

Norman de Bruijne, inventor of metal bonding.

De Bruijne was not only a pioneer in metal bonding but he also invented the fibre-reinforced plastic materials, usually called ‘composites’. In 1937, he proposed a very mouldable and light material composed of plastics and fibres. Natural fibres like cotton and flax have strength-to-weight ratios of four times that of aircraft aluminium alloys. However, it is impossible to make aircraft from fibres alone. De Bruijne’s idea was to embed fibres in a plastic such as Bakelite. In the 1930s, glass fibre was developed for this application, and this glass fibre composite was applied in the 1950s in the Fokker F-27. Like wood, composites are fibrous materials, meaning that the thread of the fibres have to run in different directions to ensure adequate strength. Like wood they have the advantage that they do not suffer from corrosion as metals do, but also suffer from the disadvantage that they absorb moisture. This degrades the material. Besides bonding, the use of composites was the second technology incorporated in Glare and it was Schliekelmann who brought it to Fokker.

Rob Schliekelmann, metal bonding pioneer at Fokker.

So far we have seen three examples of successful engineers who combined science and hands-on hobbyism: the Wright brothers, Schliekelmann from the Delft University and De Bruijne of Cambridge University. The first project Schliekelmann was assigned to was the production of the S-11 trainer aircraft. He discovered a design error in the wing that had led to a crash of the prototype in Sweden. The problem was the spar, a beam running from the root to the tip of the wing. This structural member, which had to carry the upward bending moment of the wing during flight, was built up from several parts riveted together. When this assembly of

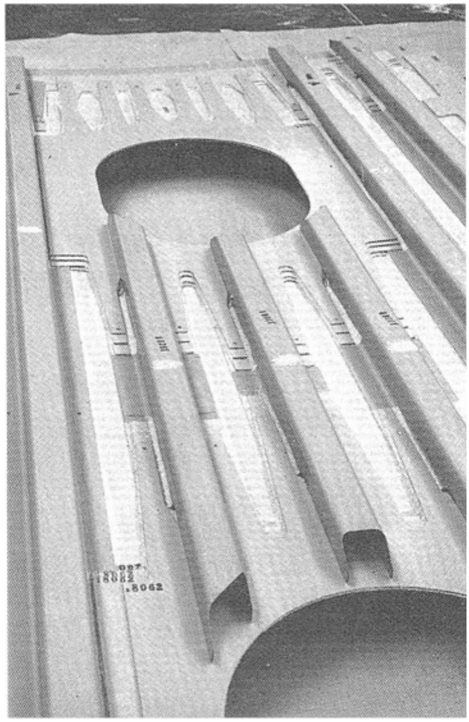
thin parts was compressed, as was the case when the wing bent upward during flight, the sheets of the S-11 spar started to buckle, no longer behaving as it had as a single thick sheet under tension. Thin sheets riveted together are weak under compression because they will buckle between the rivets. Schliekelmann found that this was the underlying cause of the fatal crash in Sweden. He was still fascinated by the metal bonding process that he had learned about while at De Havilland. He connected this new technology with the crash and realised that attachment of the thin skins in a continuous way, as is the case with bonding, instead of only locally, as with riveting, would connect the sheets more effectively. He envisioned that bonding would provide the answer for the S-11 problem. In this case, the bonded sheets would be fixed more effectively than by riveting and would react under compression in the same way as one massive sheet of the same total thickness. Tests that he carried out showed that the bonded metal sheets under compression indeed appeared to be 60% stronger than the riveted metal sheets. Moreover, a bonded package of thin sheets is 5% lighter than a massive sheet of the same thickness because the adhesive is lighter than the metal that it replaces.

The eager and enthusiastic Schliekelmann brought his superiors at Fokker to various levels of despair with his ideas of gluing metal in aircraft construction and their rejection should have brought about the end of the idea. Schliekelmann therefore leapfrogged his superiors and went straight to the most important person in Dutch aviation at the time: Van der Maas. Since Van der Maas had been his professor, Schliekelmann knew him and because Van der Maas, as a scientist, had an open mind, he was just the right person to contact. Besides, as the head of NIV Van der Maas guarded the research money. Van der Maas gave him 130,000 guilders to build and test a bonded S-11 wing, an enormous amount of research money for those days. It was Schliekelmann's intention to leap from a limited test series of small, bonded test specimens to the design, manufacture and testing of a complete wing.

However, Schliekelmann's chief was not amused by his short cut, mainly because Fokker was also trying to get money to develop its first post-war, all-metal passenger aircraft, the F-27. Van Meerten, the chief designer, raged that they had enough trouble already with this ambitious programme without Schliekelmann's new bonding project. However, Schliekelmann was finally able to convince his superiors that his bonding might in fact hold important implications for the development of the F-27.

Schliekelmann decided to try his bonding technique on the wing of the next trainer aircraft, the S-12. It turned out that a lot of craftsmanship and inventiveness was necessary to bond the various parts of the wing structure. In this process the hobbyism of Schliekelmann appeared to be of vital importance when turning the idea into reality. One of the new features was to deform a flat package of bonded metal sheets after curing to the final shape. This is much cheaper than first deforming the various parts and then bonding them together. This approach would indeed later be applied to making the bulkhead of the F-27. It took substantial effort and many hard test results from the S-12 wing project before Schliekelmann finally managed to convince his superiors in 1952 that bonding was a feasible construction technique. Even so, the NIV and KLM remained quite sceptical about the potential of metal bonding. For outsiders, the idea of gluing an aircraft together bordered on the ridiculous for a long time. Bonding suffered from its association with the glue used for paper and reeked of technology from the past. It reminded them of wooden aircraft that were built through craftsmanship rather than by industrial processes.

Fokker F-27 aircraft.



Bonded metal wing structure of the Fokker F-27.

By contrast, riveting, being mechanical, was perceived as an industrial process with visible results. One could see the two rivet heads and know that there must be a bar of solid metal in between holding the sheets together. This joining method was easier to understand and to trust. Bonding, primarily a chemical process, was more difficult to observe producing results as if by magic. Even now, the exact mechanism by which glue connects the metal sheets is not clear. The process was and is easier to understand for wood than for metal. Wood is a porous material. The adhesive flows into the pores of the wood and becomes solid during curing. The solid adhesive is therefore fixed in the pores and in this way the parts are interconnected. The oxide layers which are artificially applied by the 'anodising' process on aluminium surfaces can also have pores and may show a similar locking phenomenon as the porous wood, but it has been shown that this cannot be the primary mechanism that holds the metal parts together after curing. Perfectly polished metal sheets can also be bonded. The bonds must have some kind of chemical nature and in the thin layer

between adhesive and metal some kind of exchange of atoms occurs. It is this ‘magic’ interaction by which the materials are kept together. When the bonded parts come out of the hot press, one cannot see the complete bond line but only its edges. Dirt on the parts, grease or fingerprints, may have internally prevented bonding. None of this is visible from the outside.

Much about the high quality control needed during and after the bonding process and the durability during use of the adhesive bonded metal aircraft structures had to be learned by trial and error, and there were ups and downs. In September 1952 a static test was carried out on an S-12 wing designed by Schliekelmann as a bonded structure. The metal version had already been tested and a premature failure occurred at 4.5g due to wing bolt failures, although it was designed to withstand 7.5g.[1] The bonded wing structure could sustain this ultimate load without any problem, a result that did not surprise Schliekelmann but left the outsiders quite impressed. However, there were sometimes unexpected errors. For example, occasionally a batch of sheet metal skins with adhesive bonded stiffeners would come out of the autoclave in separate pieces after the curing cycle, as the bonding between the stiffeners and the skin had been unsuccessful. Such experiences almost killed the application of the metal bonding technology at Fokker. It turned out that the ‘anodising’ of the aluminium parts had to be carried out under closely controlled conditions. This ‘anodising’ process is an electrochemical process carried out in a fluid bath and creates a thin and very stable oxide layer on the aluminium prior to bonding. Cleaning the parts with tap water after anodising and other surface treatments was shown to be unacceptable. Testing the bond strength of small specimens bonded simultaneously with the production parts, so-called ‘witness specimens’, appeared to be essential. Inspection of final products is also necessary for quality control, but unfortunately one cannot see the bond line, as only the edges are visible. Schliekelmann was aware of this problem and developed an ultrasonic device that was able to give an indication of the quality of the invisible bond after curing; the Fokker bond tester was later used all over the world. Schliekelmann also introduced the glass fibre composites that he had first seen during his stay at De Havilland in the F-27. Schliekelmann’s achievements were surprising partly because his laboratory did not have a particularly good reputation. It usually looked a mess, and

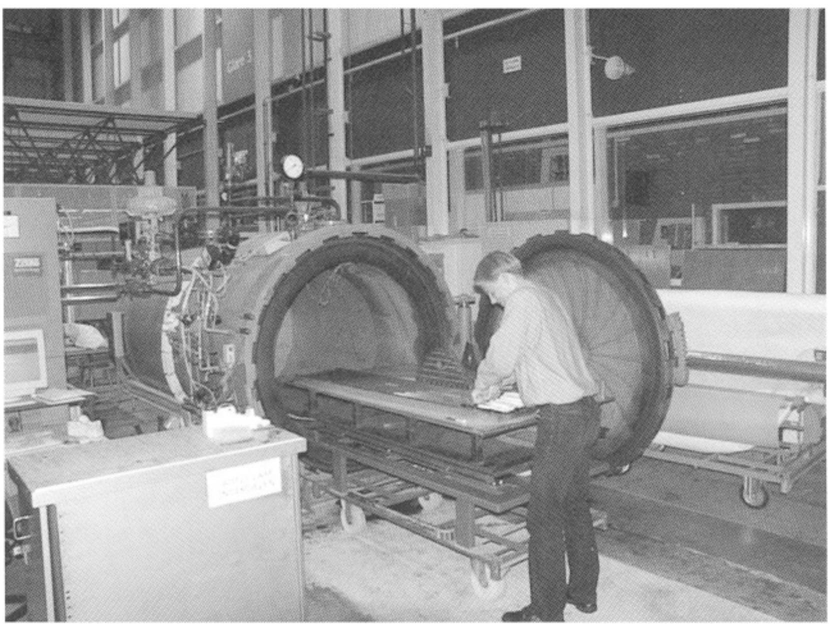
[1] Memo Falkenhagen to Dir-Gen RLD (Backer), September 1952: ARA, 5.016.01, Arch. RLD, nr. 3917.

various Fokker directors stated that the state of his laboratory was a disgrace to the company and should have been shut down.

During the early fifties, Fokker was studying the possibilities for the F-27, the first post-war commercial transport aircraft to be designed after the S-series trainer aircraft. There were many doubts as to whether Fokker would be able to manufacture such a complex state-of-the-art aircraft in an industrial and competitive way. The commercial risks taken with the F-27 were high. The aircraft was packed with new technology, which necessitated a learning process that made its development extra expensive. Embracing new technology was unavoidable, however, as the F-27 would have to compete with British and American designs from more established companies on the international market. In every respect, the F-27 tested the viability of the Fokker company to the limit.

The F-27 series production was to become Fokker's first industrial manufacturing process, but Fokker had no prior experience with so-called 'line production' – a concept introduced by Henry Ford in his car manufacturing plant after 1903. During World War II, line production had been the key innovation allowing the mass production of aircraft. Now this method of production would be vital to Fokker as a way to keep the costs of production of the F-27 under control. Moreover, Fokker lacked the expensive milling equipment necessary to produce parts from aluminium. American aircraft producers used large milling machines to make parts, for example wing panels, with a variable thickness out of a single piece of metal. The variable thickness is necessary because the required strength in the aircraft is not equal for all locations. For example, the skin of a wing has to be thicker near the fuselage than at the tip of the wing since the loads near the fuselage are higher. A plate must therefore be tailored in such a way that the local thickness required from tip to root is reached by removing more and more material towards the tip of the wing. In fact, the only way to produce these metal skins in a cheap and simple way, without having to invest in the expensive machinery necessary to remove material by milling, was by using the bonding process that originated in the home-built wooden aircraft of Schliekelmann and De Bruijne. In this way, thinner sheets could be locally reinforced by bonding other thin sheets on top of them in a stepwise fashion. Instead of removing material, as was done by their American and British competitors using expensive milling machines, Fokker decided to locally add material by bonding. Nonetheless, the problems encountered in the progress from a laboratory technology to a technology that could be used on an

industrial scale were enormous. The hot platen press that had proved useful for Schliekelmann's hobby aircraft was no longer enough. To be able to cure large panels, a twelve-metre long pressure vessel, or autoclave, was necessary. This could be heated internally and could apply a predetermined pressure and amount of heat at the right time to the parts in order to cure the adhesive. Autoclaves of that size were not available at that time and had to be custom-built for the purpose. It was Schliekelmann's idea to apply autoclaves, which had only been used industrially up to then to treat wood, for metal bonding.



Erik Kroon using the autoclave at the Structures and Materials Laboratory.

Apart from developing the necessary technology, this also involved convincing the watchdog airworthiness authorities that the Fokker solution was a safe one that would stand up to time. The Dutch airworthiness authorities, the RLD (in Dutch: *Rijksluchtvaartdienst*), started after the war with a fresh and open mind, but they had considerable reservations about the application of adhesive bonded metal structures, at least partly because experience with these structures in service was marginal at the time. However, the RLD understood that a realistic evaluation of the problems was necessary to get the Dutch aircraft industry in the air again.

Laminates under fatigue

The introduction of bonding was initially suggested because of the compression problems found in the S-11 and because of the relatively simple equipment required to be able to produce the F-27. Later it was discovered that the bonded, laminated structure also appeared to have good fatigue properties. At the time the F-27 was designed, the fatigue problem was a nightmare because of fatigue failures of transport aircraft in service. The Martin 202 lost a wing due to fatigue in its spar. Later, in 1954, the well-known accidents of the De Havilland Comet occurred. Two Comets exploded at cruising altitude as a result of the failure due to fatigue of the pressurised fuselage. The Comet was the first jet-propelled passenger aircraft and the accidents dealt a severe blow to the British aircraft industry. The Americans forged ahead to take the lead in aircraft manufacturing of transport jet aircraft (Boeing 707 and DC-8). Apart from the Comets, other aircraft also suffered from crashes connected with fatigue problems and the aircraft industry had to address the issue seriously. As a consequence, a full-scale fatigue test was carried out on a prototype of the F-27 with a flight-by-flight simulation of fatigue loads as they were assumed to occur in service. In this test, carried out in 1957, a wing failure in the centre section of the wing at the fuselage connection occurred after about 3000 flights which was a shockingly short fatigue life. Considerable research on such flight-by-flight experiments (service simulation fatigue tests) has been carried out since then. The experiments conducted by Jaap Schijve, at that time still working at the National Aerospace Laboratory NLR, indicated that the Fokker flight-by-flight tests were too simple a simulation of the complex fatigue loads occurring in turbulent air service. Moreover, the fatigue load history applied in the Fokker test was rather conservative. Fokker redesigned the centre section of the wing structure, incorporating a less fatigue-sensitive aluminium alloy (2024-T3 instead of 7075-T6).

After the modifications had been made, the full-scale fatigue test indicated a satisfactory fatigue resistance of the wing structure, although fatigue cracks were found in the outer wings. These cracks could be detected by periodic X-ray inspections before a risk of wing failure might occur. The inspection period, however, was no more than 600 flights, which was unacceptable. Fokker decided to redesign the wing and later experiments indicated that the fatigue properties of the aircraft were excellent. However, Fokker had already delivered 15 F-27 aircraft with the

old outer wing structure to different operators. Fokker decided to re-equip these aircraft with a new wing. The centre wings that were removed from these aircraft were given to the NLR for experiments, and Schijve's team carried out different types of fatigue tests on them. A major finding was the favourable resistance to fatigue crack growth of laminated sheet metal reinforcements around a large wing joint. The crack growth was extremely slow because cracks started to grow in a single layer. The other intact layers effectively bridged the crack and in this way considerably slowed down crack growth. This was an important finding for later research on laminated sheet material, as will be discussed later.

Fairchild had already built some fifty F-27s under licence, which were delivered to the operators with the pre-modification outer wings. They did not offer new wings to the airlines because periodic inspections should take care of possible fatigue cracks. One of these aircraft crashed in turbulent weather in Alaska. It turned out that X-ray pictures had been taken, but due to a communication failure the pictures were not actually examined for cracks. After the crash this was done and the fatigue cracks could indeed be observed on the pictures taken during the last three inspections. At the same time, this tragic experience emphasises that highly fatigue-resistant materials and structures are very necessary.

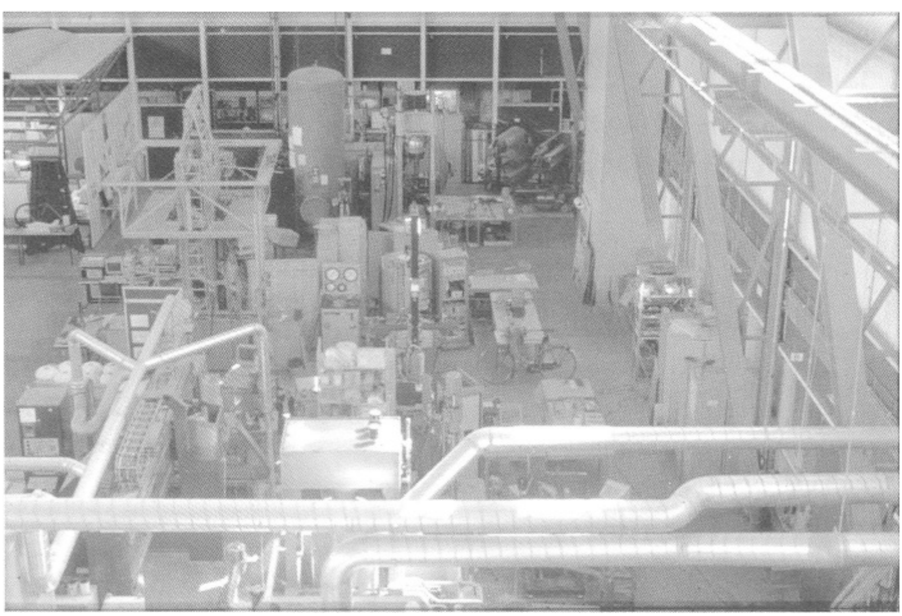
Fatigue testing in Delft

In the early fifties, Professor van der Maas thought that the NLR was in need of young engineers to work on aircraft material problems. Two students, Jaap Schijve and Harry van Leeuwen were asked to do their Master's thesis work on materials and, after graduation, to join the materials group of NLR. In 1953 Schijve started to work at NLR for Dr. Plantema, the head of the Structures and Materials Department. His assignment was to specialise in fatigue and non-destructive testing methods to detect fatigue cracks in structures, and to be involved in accident investigations. These subjects would remain the main topics of his research work for many years. When Plantema suddenly passed away in 1967, Schijve was his natural successor. In the Aerospace Faculty in Delft, Professor Spies' main interest was the study of composite materials. The Faculty wanted Schijve to come to Delft to become a full-time professor. However, Schijve initially declined the invitation because his main interest was research on fatigue. Three years

later, in 1973, Spies again invited Schijve to come to Delft. The situation both at NLR and in Delft had changed in those years. Being the head of the Structures and Materials Division of NLR, Schijve had to attend meetings of the NLR management and other committees, which left little time to be directly involved in research. Furthermore, the financial situation was also changing and was likely to change further in the future, meaning that contract research had to be the major driving force rather than research topics chosen by himself. On the other hand, in Spies' group in Delft, Boud Vogelesang was conducting research on various problems associated with the adhesive bonding of metals, chemical milling and fatigue properties of metallic aircraft materials, with graduate students contributing an essential part to the various investigations. Spies was the head of the lab, but he was not really an experimentalist and he did not feel the need for a large laboratory. Tellingly, Spies' office was in the main building of the department, on the fifth floor, miles away from where things actually happened. Spies primarily cherished the collection of aircraft and aircraft parts that had been assembled for study in the laboratory building, while Vogelesang leaned more toward experimental research.

Overview of the study collection in the Structures and Materials Laboratory.

Vogelesang was also a graduate from Delft. After completing his studies, he had planned to go to the U.S. to work for Boeing on its project for a supersonic transport, the Boeing 2707. However, this project was cancelled in March 1971, which meant that Vogelesang stayed on in Delft where he had already worked as a student assistant in the materials lab. Vogelesang had started his scientific career with test work on etched aluminium, in co-operation with Paul Bijlmer of Fokker, and on adhesive bonding. Etching was used as a production process, similar to milling but using chemical methods to locally reduce the thickness of the sheet. When Vogelesang joined the laboratory, it had no equipment and consisted of some tables that were used to bond specimens together. Together with Theo de Jong, he managed to expand the lab gradually over the years, winning lab space of other research groups and reducing the size of the study collection, reflecting a strong policy of expansion. The first fatigue-testing machine that he managed to obtain for the lab was a 20-ton Amsler, which was discarded by the NLR and was shipped to Delft with the help of Schijve of the NLR.



Overview of the area with test machines in the Structures and Materials Laboratory.

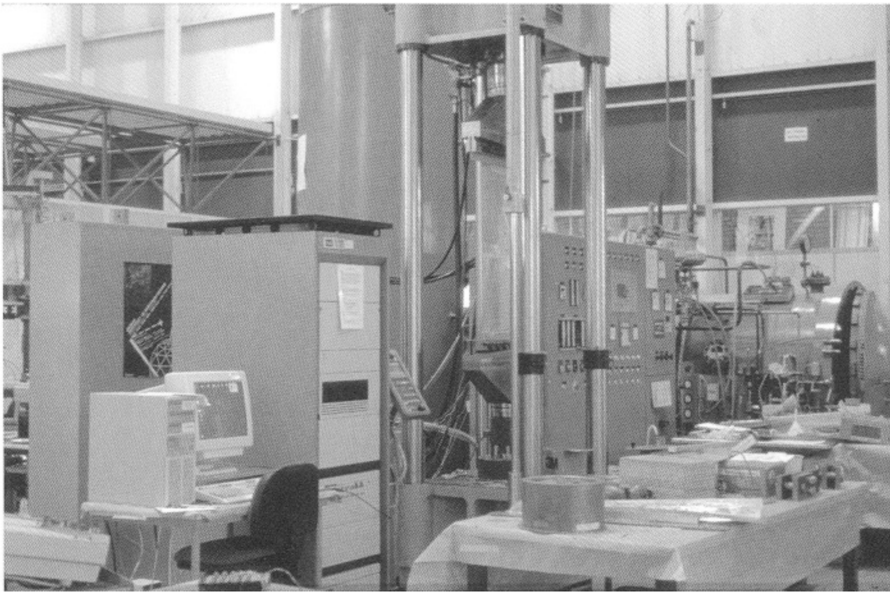
Frans Oostrum searching for fatigue cracks in a specimen in the 20-ton Amsler test machine.

A small home-built fatigue machine – the ‘6-ton’ – had also been built and the first closed-loop fatigue machine was installed in the laboratory and controlled by computers for realistic flight simulation testing. In view of these circumstances, Schijve thought that the conditions for research in Delft looked promising and he moved to the university. It was the beginning of some exciting years of close co-operation between Schijve and Vogelesang, who put together a team that generated numerous research projects and worked with a group of lively and enthusiastic students.

One early project that is worth noting was associated with laminated sheet material, although still without fibres. Experiments conducted by Bijlmer at Fokker had already shown that the fracture toughness of such laminates was superior to the fracture toughness of thick monolithic plate material. In Delft, several research programmes were conducted to look at fatigue crack growth, comparing a laminated material consisting of 5 sheets of 1 mm thickness of aluminium 2024-T3 to a single sheet of monolithic material of 5 mm thickness. The first tests were carried out as a part of the Master’s thesis project of Harry van Lipzig. He showed that crack growth in laminated specimens was significantly slower than in monolithic plate

material. Another student, Harry Hoeymakers, observed that this was also true for fatigue cracks in lug specimens, representing a single bolt connection. The Master's thesis project assigned to Berry van Gestel was associated with fatigue crack growth experiments on laminated specimens starting with an initial fatigue crack in only one of the outer sheets of the laminated material. Such a crack represents a surface crack of the laminate. An experimental trick used in this project was to measure crack growth in the invisible sub-surface layers of the laminate. This could be achieved by adopting the so-called potential drop method for each layer of the laminate. The most remarkable result was that the crack growth in the outer layer, was slowing down after some initial growth. Because the crack had not yet penetrated into the sub-surface layers, crack opening of the fatigue crack in the surface layer was effectively restrained, reducing the stress intensity at the crack tip in the outer layer. The inner layers were bridging the fatigue crack of the outer layer. This behaviour was similar to the earlier observations made by Schijve on the pre-modification F-27 wing panels. Shortly afterwards it would be shown that the bridging effect can be considerably enhanced by incorporating fibres in the adhesive.

6-ton fatigue machine with equipment in the Structures and Materials Laboratory.



100-ton fatigue-testing machine of the Structures and Materials Laboratory.

Adding fibres to adhesive

The construction of the F-27 incorporated metals as well as composites, i.e. combinations of glass fibre and plastic. In the 1950s, composites were studied extensively all over the world. The combination of carbon fibres with plastic, also invented in the 1950s, was especially promising because of its extremely high strength and stiffness and low weight. However, the introduction of composites in aircraft required a revolution in aircraft design and manufacture at a time when the manufacturers had invested in and were gaining experience with metallic structures. It would take decades before successful applications could be realised, partly because composite materials also suffered from some disadvantages. Although composites were very expensive, their potential was clearly recognised. Against this background, combinations of metal and composites were being studied in Great Britain and America as a kind of intermediate between wholly metallic or composite structures. British researchers bonded composites as reinforcements on rods, tubes and beams in the early 1970s and measured the efficiency of the combinations compared to aluminium. For them, the lower cost of the combination

compared to full composites was important. The NASA Langley Research Center also emphasised the lower cost and treated the reinforcement as a way to reduce the weight while simultaneously reducing the risk of applying a completely new material. NASA researchers were especially interested in using local reinforcements bonded to aluminium structures for Space Shuttle components.

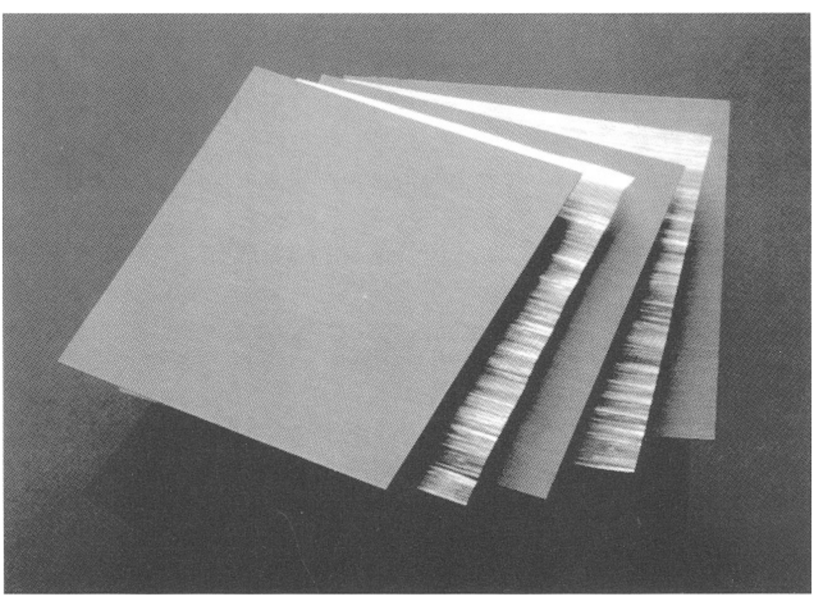
Some of Schliekelmann's co-workers at Fokker saw these tests during a visit to the U.S. at the end of the sixties. The space division of Fokker received a contract from NASA to perform a study, together with Schliekelmann's department, on the feasibility of using doors for the Space Shuttle made from laminates of titanium and layers of fibres embedded in an adhesive. The Philips laboratory in Eindhoven was also involved as it could produce the very stiff boron fibre. Results for these fibre-metal laminates were published in 1971 and 1972.

In 1973 Cools' metal group worked under Schliekelmann on a combination of metal reinforced by composites to increase the stiffness of metallic structures. At that point fatigue was still not an issue. The other group reporting to Schliekelmann – the structures group headed by Bijlmer – started to work on fracture toughness of bonded laminated structures. The research focused on the addition of fibres to the adhesive of the laminated structure that was typically used for Fokker aircraft in 1974. A similar combination of composites and aluminium could be achieved, in this case by starting from the bonded metal laminated structure of the F-27 and adding fibres to the bond line. In this way the adhesive performs another function in addition to keeping the metal sheets together, reinforcing the aluminium like the reinforcement of concrete. It positioned composites even closer to the well-established technology of bonding at that time. Paul Bijlmer was leader of the project that was set up to study this. Nylon fibres were applied as a weave, while carbon was used in a single direction (unidirectional) embedded in bond lines between one-millimetre thick sheets. The fatigue crack growth properties of those fibre-reinforced laminates were determined. Under constant-amplitude fatigue loading some reduction of the crack growth rates was obtained, which was more significant for the carbon fibres than for the nylon fibres. The strength of the material after inflicting large amounts of damage in the form of saw cuts was measured to determine the damage tolerance of the laminates. It was well known from earlier experiments done by Schijve that the damage tolerance of a laminated sheet was higher than that of a single massive sheet, but it was found that this

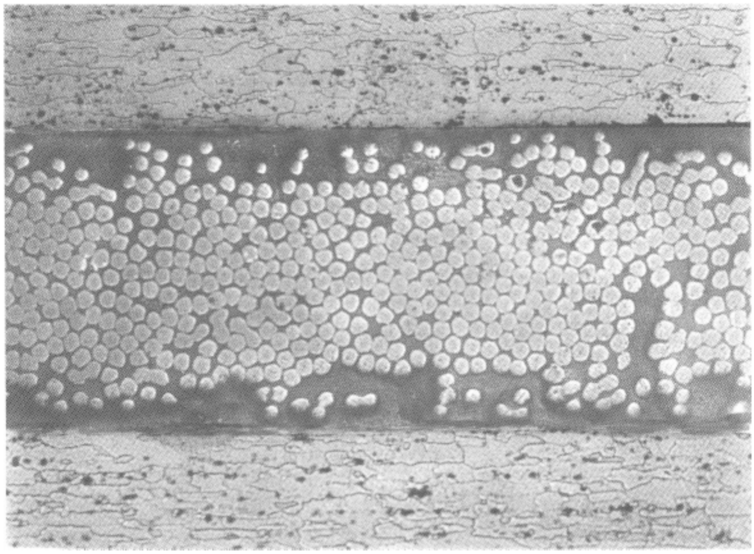
tolerance was even further improved by adding fibres to the adhesive. The fibres added strength to the laminate, while the metals provided strength perpendicular to the fibre direction. As explained earlier, to make his composite wings Anthony Fokker had to bond various layers of wood together to get strength in all directions. In this case, the metal could provide strength perpendicular to the fibre. Crack growth in the fibre-reinforced laminates was two to three times slower than in aluminium but this was not enough to offset the high cost of the material. The concept of fibre reinforcement was technically very interesting, but the results were not spectacular and the many inherent problems related to durability and quality control which Schliekelmann had managed to solve for application of bonding in the F-27 seemed to be endless and would lead to expensive products. Almost from the start, Delft was involved in these developments and the discussions that took place. Schijve and Vogelesang gave student Lex ten Have the task of carrying out flight simulation tests in 1978 on carbon and aramid fibre-reinforced laminates. The unidirectional carbon fibres remained intact under these conditions, whereas the aramid fibres that were applied as a weave broke at some distance from the crack tip. The completely intact carbon fibres, which were all aligned in the loading direction, slowed down the crack growth considerably, much more than the only partly intact aramid fibres of which only half were oriented in the loading direction.

Fokker took a new approach, which was to reinforce the adhesive with fibres instead of reducing the fatigue crack growth of the aluminium layers by crack bridging with fibres. In the latter case, the Delft philosophy, the selection of fibres and layer thicknesses leads to a different approach. The activities at Fokker were stopped by Schliekelmann. His decision was based on the fact that Fokker had no new aircraft under development at that moment and the intention was to replace the current adhesive layers in the structure with adhesive containing fibres. It appeared that it was not possible to do this without full-scale tests and a new certification of the aircraft, which was far too expensive. In Delft, Vogelesang was very much in favour of continuing the development of the fibre-metal laminates with crack bridging as the ‘leitmotiv’. He continued the contact with Bijlmer of Fokker in spite of the initial scepticism of Schijve, and Bijlmer continued to work in secrecy in spite of Schliekelmann’s decision. It had become clear to them both that fatigue in the fibre-reinforced metal laminates was a delicate process. Evidently, loads from the cracking metal layers were transmitted via the

adhesive to the fibres, thus unloading the metal layers and slowing down crack growth in these layers. This is called ‘fibre bridging’. It was subsequently found that the adhesive, which is loaded in fatigue, started to separate from the metal. This process is called ‘de-lamination’, since the various layers become loose when the adhesive fails. At first glance, this release of the bond seems bad. However, without this delamination the fibres would be stretched too far when the crack is opened and would break. If on the other hand the delamination is too large, then the crack will open too far and the crack will consequently grow too fast. Therefore, there is a balance between delamination and crack growth that is assured by the strength of the adhesive and its resistance to delamination. This balance must be established over the whole length of the crack, since if at a certain location the loads in the fibres are higher than elsewhere, more delamination will occur there and this will reduce the load on the fibres at that location. The intact fibres in the wake of the crack considerably restrain the opening of the fatigue crack, which has a most favourable effect on the stress intensity at its tip. As a result, fatigue crack growth is effectively slowed down, and even full arrest of crack growth can occur. In this way, insight into the mechanism evolved slowly, making optimisation of the fibre-metal laminates possible.



Fibre-metal laminate build-up.

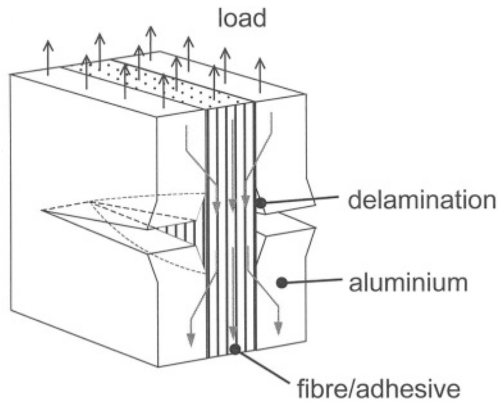


Close-up of a fibre-metal laminate cross-section.

Another Master's thesis project was defined to examine this problem and assigned to Roel Marissen. Marissen was an ambitious young man. Up to this point, he had not particularly enjoyed his studies at Delft. Although the research at Delft had practical applications, the curriculum itself was highly academic and theoretical. This was a legacy from the period when Delft had to fight for its academic status amidst the general universities in the Netherlands. A solid scientific basis for the course of study was a way to achieve this, although many of the graduates might never again use the theories they had learned. The emphasis on theory disconcerted Marissen. The reason he chose to attend Delft was a meeting in the lab of the aerospace department when he was still in high school. One of the professors, Spies, the specialist in composites, had taken the time to explain what lab facilities Delft had to offer. Spies' enthusiasm hit home and kept Marissen loyal to Delft throughout the theoretical part of his study. The enthusiasm for composites of Spies and the inspiring way Schijve could teach about fatigue cracks perfectly matched the material Marissen wanted to study for his Master's. When he became involved in Schijve's and Vogelesang's project on fibre-metal laminates he was finally able to do work that mattered and in an environment that treated all student research with utmost seriousness. It appeared to be the perfect setting to ponder the development of a new material.

His experimental programme covered sheet metal laminates both with and without nylon fibres. The laminates without fibres were included as a reference to allow any improvements obtained to be more easily quantified. Carbon fibres were not considered because it was expected that corrosion problems could be significant in view of the electrical conductivity of these fibres. Furthermore, aluminium alloy sheets with a lower thickness were desirable in order to reduce delamination and enhance the fibre bridging effect. 0.6 mm sheets of the alloy AU4G1 were available, an alloy very similar to the well-known 2024-T3 alloy. Sheets of a still lower thickness were needed but were not yet commercially available. They had to be machined from sheets with a larger thickness, which was done by chemical milling; an etching process on which Vogelesang had worked in the past. Marissen carried out flight simulation fatigue tests on specimens with a central crack or a central hole. In a second test series he did constant-amplitude tests on lug specimens of the same dimensions as those used by an earlier student, Hoeymakers. Another variable was the application of post-stretching. The curing cycle of the fibre-metal laminate occurred at 120°C and cooling down to room temperature introduced residual stresses due to different coefficients of thermal expansion. A residual tensile stress occurred in the metal layers, with some compression in the fibres. In spite of this unfavourable residual stress system, the crack growth results of Marissen were still very promising. However, the residual stresses could be reversed to create compression in the metal layers and tension in the fibres through a post-stretching operation applied after curing. This was achieved by stretching the fibre-metal laminate to a small plastic strain in the metal layers while the fibres remained elastic. When this was done, the aluminium layers would elongate permanently while the fibre would remain elastic and would want to return to their original length. This counteracted the stresses that were present in the material after curing. Tests conducted by Marissen confirmed that the post-stretching treatment further improved the crack growth resistance of the fibre-metal laminates.

Crack bridging by fibres implies that some load transmission must occur between the metal layers and the fibres, causing shear stresses in the adhesive between the fibres and the metal layers. As was described above, some delamination around the cracks can therefore occur and this was indeed observed by Marissen in ultrasonic transmission (C-scan) pictures of his specimens.



Bridging of a fatigue crack in the metal layers by intact fibres.

Marissen developed an analytical model for the prediction of fatigue crack growth in fibre-metal laminates based on fracture mechanics principles. The stress intensity factor of the fatigue crack was calculated using this model, which accounted for the fatigue cracks in the metal layers and the crack bridging load of the unbroken fibres in the wake of the crack. Marissen had to make some simplifying assumptions in his model, but it was based on a physical understanding of the observations on the mechanism of crack growth in the fibre-metal laminates. It turned out that the agreement between predicted crack growth rates and observed crack growth rates was encouraging. It substantiated the basic concepts of a new class of fibre-metal laminates characterised by (*i*) bridging of fatigue cracks by high-strength fibres and (*ii*) thin metal sheet layers allowing for more fibre layers, reducing the shear stress in the adhesive between the fibres and the metal layers and therefore limiting delamination. Vogelesang christened the material with the acronym Arall (Aramid Reinforced ALuminium Laminates).

To avoid interruption of his work on laminates, an assignment for practical training was arranged by Vogelesang and Bijlmer, and Roel Marissen left to work at Fokker for a couple of months. When he returned, the relations were not optimal since Fokker had presented his modelling work at the ICAF symposium as ”Crack Propagation in Multiple Layer Adhesive Bonded Material” in 1979 without so much as crediting his contribution, much of the work for which had been carried out at Delft.

The superior crack growth characteristics of improved fibre-reinforced laminates had slowly become evident, but a real understanding of the cause of this superior behaviour had to come from theoretical analysis. That was one of the important results of the work done by Marissen. This could also lead to better fatigue properties, since fibre-reinforced bonded laminates still suffered from the high cost of adding fibre to the bond line. Marissen's modelling work made clear what was happening inside the fibre-reinforced laminate. It also showed how this mechanism could be optimised. When the metal layers are too thick, the loads in the adhesive will be too high and too much delamination will occur. In such cases, the crack bridging could not be effective. This insight opened the way to even better fatigue properties. Thinner sheets were not yet commercially available, although the model showed that this would be favourable. Therefore a process was used to dissolve part of the aluminium on the outside of the sheets through etching. Together with helpful lab technicians, they managed to manufacture the laminates and specimens and test them with the simple equipment that they had available in the university lab. This was an ideal combination of the work of Schijve's metal, fatigue and bonding group and the composites group of Spies. Van Dreumel of Spies' group assisted Marissen with manufacturing the fibres to be used with the adhesive. This was unique because the metals and composites research communities usually competed with each other, with the application of one material type displacing the other from the aircraft. Nonetheless, a mild sense of competition between both 'blood groups' in the structures and materials lab remained. This was expressed in jokes from the composites camp like "Why don't you remove the metal packing from the nice composite layers? In that case it will not crack at all!" In a sense this was true. Composites suffered far less fatigue than metals. In a way the metals community liked the way the fibre-reinforced laminates cracked because it resembled the behaviour of their metals and they could do fatigue tests on them.

A lot of hobbyism was required in the lab to develop Marissen's laminates. Fibres had to be laid over an adhesive film by a winding process using a simple, modified lathe. Aluminium had to be etched, anodised and primed before bonding. After laying up the various layers, they were cured in a hot platen press. Specimens had to be fabricated, mounted in the test equipment and tested for fatigue resistance. The development involved a lot of laborious work that at first sight did not appear likely to change the world of aircraft structures. The tests carried out by Marissen were very time-

consuming because crack growth was extremely slow. Whereas the reinforced laminates developed by Fokker had improved the lifetime by a factor of two to three, crack growth could now be reduced by more than an order of magnitude – 10 to 100 times slower. After post-stretching, the crack growth in the material even stopped. As a consequence, Marissen's Master's thesis project took a lot of time, and eventually Schijve told him "Please write up everything in your Master's thesis, get your diploma and find a job". However, after a difficult start to his study in Delft it was now difficult to stop him. "Power over matter is addicting", he would quip. Roel therefore asked permission for just one additional test on a lug specimen made of Arall, which he carried out between Christmas and New Year's Eve, 1979. After four days of testing in the fatigue machine, just before New Year's Eve Marissen told his professor that the crack had grown no more than 2 millimetres in some 4 million cycles, an exceptionally slow crack growth. This caused some excitement in the lab in the first days of 1980. The crack hardly grew! The ability to reduce crack growth rates to less than one hundred times below that of normal aluminium was now within reach. Later, working in a German aeronautical laboratory, Marissen wrote a doctoral thesis on an improved and more detailed model for fatigue crack growth in fibre-metal laminates.

Delft in a new role

With the Arall concept and this new insight, the future for the fibre-metal laminate looked bright. Its exceptional resistance to fatigue looked like being a major advantage arguing for its application in fatigue critical aircraft components, and the number of such components in an aircraft is large. However, it was clear to Vogelesang and Schijve that a lot of development research remained to be done before the new material could be considered for application in aircraft structures. Unfortunately, at the same time the first cracks in the relationship between Fokker and Delft appeared in the conflict around the publication of Marissen's work. To understand this, one should realise that after the war the aircraft-manufacturing infrastructure was arranged in such a way that there was a clear division between the three major organisations: Fokker, NLR and Delft. Every activity of this triangle was aimed at the well-being of Fokker since this major player had to build the aircraft, without which there was no apparent need for either aeronautical

education or research. Delft's primary role was to provide good quality engineers to serve the needs of Fokker and the NLR. The NLR would do the research and part of the development to support the design of aircraft, which the NIVR financed. This theoretical division of responsibilities did not work because it separated, and therefore isolated, the tasks too much. Many research reports of the NLR communicated excellent scientific work, but in too many cases were buried in the archives of Fokker. Delft did an excellent job in educating young people, but was supposed to act too much as a company school tailored to the needs of Fokker and NLR. As the NLR and Delft University became more and more mature, their need to have their own identities within the Dutch aviation community and the international arena grew. Initially, the graduates from the aerospace faculty were to a large extent employed by Fokker, but by the 1970s and 1980s less than fifty percent of Delft's new engineers found jobs in the Dutch aerospace sector. A major readjustment came in the late 1970s when the government policy for universities started to change. The Minister of Education proposed that universities should earn part of the money they needed for research by obtaining outside contracts. This meant that Delft University had to change from a pure science, non-profit organisation to an organisation with some of the characteristics of a company. It also meant that the universities were thrust into the midst of growing competition for funding between the various university research groups and the research institutes, such as the NLR and TNO. In 1981, it was reluctantly admitted in an NLR memo concerning the prospects of research into fibre-reinforced laminates, that the Minister of Education now required that Delft University acquire remunerated projects. According to the memo, this could easily lead to unfair competition, as the university could operate more cheaply than a research institute like the NLR, partly because of the contributions of students to research programmes as part of their thesis work. It was also evident that when Delft was emancipated in this way, a conflict with Fokker was bound to occur. Delft University had to acquire projects from foreign competitors and might therefore work against the interests of the Fokker company. Fokker at that time did not consider Arall to be a potentially useful material for designing lighter aircraft structures, and thus did not see why research efforts on the development of Arall should be sponsored. However, Vogelesang and Schijve were eagerly looking forward to further developments of Arall, a material born in Delft. They were very committed to carrying on the research in the lab in Delft, with the challenge of developing a fatigue resistant

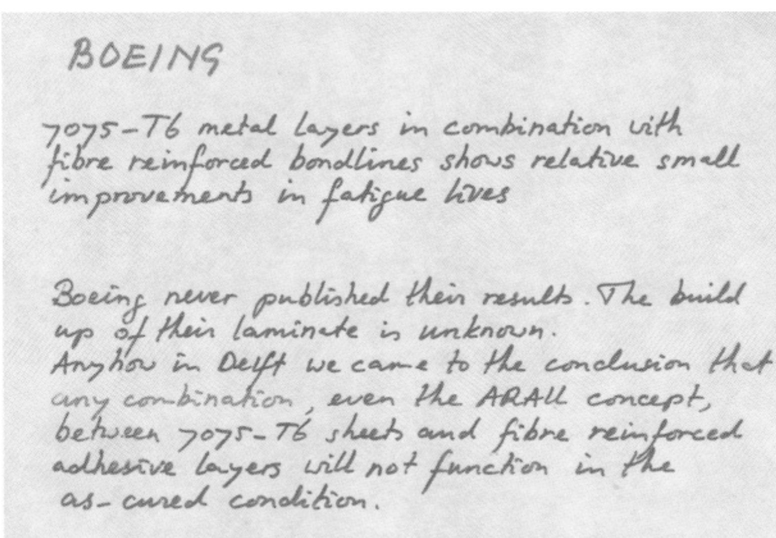
material for aircraft structures. They were convinced that they could contribute to this development, although they also realised that co-operation with the aviation industry was essential. Unfortunately, the disconcerting and conflicting interests led to difficult discussions for several years in the 1980s.

A good idea is one thing and to realise it is another, but to convince the whole aircraft manufacturing world that fibre-metal laminates were the way to go is something completely different. It requires a strong belief, a convincing story, and a great deal of stamina. Boud Vogelesang was the man who would provide this during the years to come. With Schijve's international reputation on fatigue coupled to Vogelesang's strong commercial instincts, the new material had a chance to succeed. Without this unique combination, the idea of fibre-reinforced metal laminates might well have been filed in the Fokker archives, never to show its potential. Invention of a new technology is just a tiny fraction of the work. The struggle for acceptance is the major part. Vogelesang was not only an excellent scientist and an engineer but he was also able to convey his findings in a very convincing way. That is a scarce combination. Scientists and engineers are generally specialists rather than people with a broad vision, and are seldom good communicators and ambassadors for their message. It was said of Vogelesang, with respect, that he could sell a fridge to an Eskimo. In a sense this was just what he had to do, because the rest of the aviation community absolutely did not feel the need for a glued material mixed with fibres.

From the beginning of the research on fibre-metal laminates in Delft, it was clear that the production of the laminates required other partnerships than that with Fokker, as had been the case in the past. The obvious needs were associated with strong fibres and thin aluminium alloy sheets. The large Dutch chemical company AKZO manufactured aramid fibres suitable for the laminate, so Vogelesang contacted the research managers there and built up useful contacts with AKZO, which showed a great interest in the Delft work as their fibres could be used. Vogelesang also contacted ALCOA, an American aluminium producer, through Bob Bucci, an old friend of Schijve. He thought they might be able to produce thin aluminium sheets, i.e. thinner that the 0.6 mm used by Marissen. Arall was interesting for ALCOA since the company was afraid that at some future date composites might replace aluminium altogether. The laminates contained less aluminium, but at least it was still there.

Vogelesang also realised that it was imperative to find a manufacturer that could produce the specialised combinations of adhesive and fibres (called ‘prepregs’) that the project would need. He made initial contacts with 3M, which made good adhesives and was also able to manufacture the prepregs. Vogelesang not only excelled in scientific analysis and experimental research; one of his major achievements was to establish good relationships, both in the corporate and in the personal sphere.

During 1980, other students became involved in optimising the fibre-metal laminates. Finally, a layup was selected using aluminium layers of 0.3 or 0.4 mm thickness. Two aluminium alloys were tested: type 7075, an aluminium alloy with high strength but relatively poor fatigue properties, and 2024, an aluminium alloy with lower strength but with superior fatigue properties. For the 7075 variant stretching after curing was necessary to get good properties, while for the 2024 laminate curing alone appeared to suffice. The more detailed contours of the new material now began to take shape. For a laminate with aluminium, fibres and adhesive, many variants were theoretically possible. Research, however, soon focused on specific variants with AKZO’s aramid fibre, two aluminium alloys (2024 and 7075) from ALCOA and an epoxy adhesive from 3M.



BOEING

7075-T6 metal layers in combination with fibre reinforced bondlines shows relative small improvements in fatigue lives

Boeing never published their results. The build up of their laminate is unknown.
Anyhow in Delft we came to the conclusion that any combination, even the ARALL concept, between 7075-T6 sheets and fibre reinforced adhesive layers will not function in the as-cured condition.

Overhead sheet used by Vogelesang to defend the patent against Boeing in April 1984.

The bonded laminates used on the Fokker F-27 could not be characterised as a material. It was a structure: a bonded assembly of different parts. With the industrial partners ALCOA, AKZO and 3M – all material manufacturers – the fibre-reinforced laminates were no longer a structure but a material: a so-called 'semi-finished product', similar to a regular sheet of aluminium. This represented a definite change of perspective. Instead of producing the laminates themselves, aircraft manufacturers like Fokker would in the future have to buy the fibre-reinforced laminates from, for example, ALCOA.

These were the first steps the Delft group took into the commercial world, which is completely different from that of the research laboratory. The natural reaction of a scientist is to tell the world about his spectacular findings. Vogelesang, eager to present his findings, therefore submitted a paper with Marissen as a co-author to a conference in Cannes in January 1981. However, AKZO urged Schijve and Vogelesang to file a patent first. AKZO was producing the aramid fibre under the name 'Twaron' and its production was still far from a commercial success. Therefore Arall was of commercial importance for the company. AKZO was a chemical firm and aircraft materials were a new business for them, especially because the fashion in the early 1980s was to strive for diversification of the product range. An aircraft material was important to them as a high-tech product that would add lustre to AKZO's whole range of products. It led to a close and very fruitful co-operation between AKZO and Delft for years to come. The university did not have much experience with patents at the time, therefore AKZO filed the patent. At the university's administration building, Vogelesang was even told that it was *not done* to file patents as a university. Pure science was still the ideal in those days. An agreement was reached that AKZO would sponsor the research in Delft in return. The patent was filed in the U.S. on the 9th of January 1981. As inventors of the new material it credited Schijve, Vogelesang and Marissen. Actually there were two patents: a general one that defined a combination of metal sheet and fibres and a separate one on the stretching process. If the first failed then the second one would certainly be new. Sheet thicknesses covering a range between 0.3 and 0.7 mm were specified to avoid conflicts with Fokker's work and also earlier work on non-optimised, aluminium structures strengthened by composite layers done in Britain and in the U.S. The name of the applicant is Delft but AKZO holds the rights. The filing of the patent had to be done

quickly and was just in time for Vogelesang's presentation of the results in Cannes in January 1981.

Both patents were granted, but not without a fight. The claims had to be revised after an attack from Boeing. In April 1984 Vogelesang had to fly to the U.S. to be interviewed by an examiner of the Unites States Department of Commerce in order to defend the claims in the patents. This was tricky, since Fokker, British Aerospace and Boeing had all published work on laminates with fibres. The optimisation process that had led to the exceptionally high fatigue resistance of the Delft laminates had to be explained. The minutes of this interview state that the examiner was "favorably impressed by the presentation of Mr. Vogelesang". This was not an easy task since it required convincing evidence in front of a critical jury on a case that was not straightforward. Others had worked on fibre-reinforced laminates, but they had not developed an optimised configuration in the form of a material with a fatigue crack bridging mechanism. One could say that he had managed to 'sell his first refrigerator'. It was not without reason that in 1983, Vogelesang was nominated by the journal *Aviation Week & Space Technology* for an award for his Significant Contribution to Aerospace with the words: "for continuing, with his students, his research into weight-saving aluminium/aramid materials after others gave up".[1]

[1] Aviation Week & Space Technology. January 2, 1984, p.9.

2

Arall takes to the air (1981-1988)

Durability

Fibre-reinforced bonded laminates, launched in Delft under the acronym Arall, were promising new materials for aircraft structures. However, there was still a very long way to go. To ensure safety, more test data on different characteristics were necessary. These in turn gave rise to new questions and uncertainties, necessitating yet more research. Primarily, the aviation community had to be convinced that Arall was a viable material. Although the good news regarding the Delft invention was becoming more widely known, reaching the highest levels of management in the international aerospace industry took time. There was no shortage of objections to the new material in the aircraft industry. Specialists in corrosion protection did not like the untreated edges of Arall, specialists in drilling would complain about drills wearing out sooner during production and that special drills had to be developed, inspection specialists were suspicious of the different layers of the laminate since it hampered the detection of hidden

cracks, and so on. There were so many obstacles that the task seemed almost impossible. Every new hurdle could kill the new technology and all the conditions had to be just right for the project to succeed. This dissemination process took years and could only be completed because, as a university, Delft was able to finance this type of long-term development by incorporating the research into Master's thesis projects and using existing staff as supervisors. It also required the broad technological basis in Delft to respond to all the different questions that were raised. Had Vogelesang not continued to push everyone at Delft, the new concept would have been abandoned the same way as it had been at Fokker. He would not hear of any setbacks: "Yes, I know it is busy and stressful now. Still one more year and then...." "Yes, this is a negative aspect of the material, but if you do this or that and look at the bright side..." It was this attitude that kept the project going for more than twenty years.

To illustrate the scepticism that had to be overcome, one only has to read an internal memo that circulated in a company during this period:

> "This type of material has great potential; however, 7XXX or 2XXX aluminium sandwiching aramid fabric and held together with epoxy resins has such a potential for catastrophe that it is not a question of if it will fail but only how soon it will fail. The epoxies are cracked, the aramid is hygroscopic, the aluminium corrodes, the lamina will disbond, and the compression strength of the part will cease to exist... Arall as it is presently constructed is not worth testing."

This quote has a seemingly technical content but also hides strong emotions and beliefs. With 'epoxy' this critic pointed to the type of adhesive used in Arall. People had to start to 'believe' in the new material. 'Belief' was the operative word here, because as long as the material had not been applied and proven in service, all it had to show were some ambiguous research data from a small lab in a tiny country, presented in a graph. Confidence had to be nurtured and given a chance to grow, and a lot of research had to be done to gather all the relevant data on this new material.

Up to this point, much of the research had focused on the fatigue tests from which static strength data had been obtained. A broad variety of properties were still unknown: long-term behaviour, workshop properties, residual strength, behaviour of joints, economic viability, and so on and so

forth. In September 1980, an agreement was reached between Fokker, NLR and Delft to co-operate on further research. Unfortunately, the activities remained primarily limited to Delft. Although Delft had a good reputation in the aerospace world, it was only a university. To convince the world, strong support from aircraft manufacturers and even governments would be needed. In 1981, an agreement was reached between AKZO, ALCOA and 3M to produce and market the material. ALCOA and 3M contributed by making special ingredients for Arall to be used in Delft, while AKZO supported the research in Delft with a grant of 100,000 guilders per year. In December 1981, a request for support was filed with the Dutch Ministry of Education and Sciences through the STW research foundation for the technical sciences. This request was granted. With this money Delft was able to hire a technician, Kees Paalvast, and a PhD-student, Marc Verbruggen, for the project. The extra brains and hands came not a moment too soon, as the biggest concern for Arall had to be tackled forthwith: would the material keep its excellent properties during 25 years or more service in hot and humid conditions. After all, the economic life of a modern passenger aircraft was expected to be at least a quarter of a century. With support from STW, Verbruggen's PhD-research focused on durability. STW would continue its support to the very end, right up to the application of the material in the A380 in 2001. Within this partnership ALCOA'S input was essential, because with over 80 percent of a civil aircraft being made from aluminium, it had the world's biggest market share in the production of aluminium used in the aircraft industry. The most important aluminium alloy, 2024-T3, was still the same as that used in the 1930s for the first American metal aircraft. Fifty years later, this alloy was still almost unrivalled. ALCOA was also capable of producing thin sheet material in the required dimensions. Up to the end of the 1990s this company, together with the producer Kaiser, was the only manufacturer that could produce sheets of 0.3 mm thickness that were more than one and a half metres wide. Other aluminium producers, like the Canadian ALCAN and the French Pechiney, were limited to a width of 70 centimetres, which would require many joints in an aircraft.

Delft University lacked the experience that would enable them to gather the required evidence over a broad range of different specialist areas to further develop the laminates. The laboratory was primarily equipped to perform fatigue tests; equipment was scarce and manpower limited. Nonetheless, the first progress report to STW, written in 1982, already mentioned an impressive array of work that had been carried out: the design

of a Fokker F-27 wing panel, the design of an F-27 wing lug, the design and testing of stiffened panels, fatigue tests on bolted and bonded joints, blunt notch strength, durability and corrosion research, corrosion fatigue, relaxation of internal stresses, the production of Arall, and the list went on. The reference list already contained 25 reports. In 1983, a lot of optimisation work was carried out by investigating the effect of different types of aramid fibres, primers, and types and thicknesses of aluminium layers. The first durability investigations were carried out by Verbruggen.

In one of his tests, Verbruggen tried to measure the moisture absorption in Arall. The epoxy adhesive in which the fibres were embedded absorbed water, thus reducing its strength and more importantly the adhesion between the fibres and the epoxy adhesive. He exposed specimens to different environments: air, immersion in salt water, immersion in distilled water, etc. These environments were meant to simulate worst cases and so accelerate the tests. The problem was how to simulate thirty years of aircraft use in a single year of testing. This was problematical, as in reality an aircraft experiences many cycles of temperature and moisture content of the air. The effects of such cycles had to be tested. Although this cycling could be accelerated, it was feared that fast cycling might not have the same effects as slow cycling, as penetration over a longer period of time could, in principle, produce more severe negative effects on the material. The only way to be certain of the durability of Arall was to use it in a real aircraft, but to be able to do so, the Delft scientists needed to convince the airworthiness authorities that Arall possessed satisfactory durability. This was no easy task. Indeed, had the same level of airworthiness confidence been necessary in the case of the application of aluminium instead of wood in the 1930s and of the bonding technology at Fokker after the war, such developments would not have progressed from the laboratory to actual aeronautical practice. Since 1945, the effort required to get new materials accepted for aircraft construction had grown exponentially – and to such an extent that a well-known scientist predicted: "This is the last time that a new material for primary structures will be applied on an aeroplane!" after the first application of Glare on the A380.

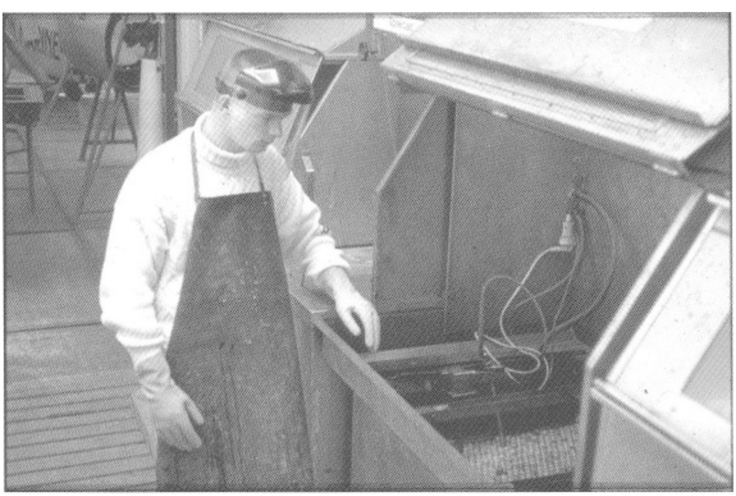
In Arall, the fibre/epoxy layers are protected by the aluminium layers, and therefore the process of the penetration of water into the adhesive, which occurs mainly along the fibres, was very, very slow. This is the advantage of Arall over composite materials. Verbruggen had to measure the weight of his specimens with an accuracy of 1/1000th of a gram. Often he

measured weight loss instead of weight gain after immersion in water, because dust particles which were present on the specimen when he measured the weight the previous time fell off the specimens when he measured the weight one month later. Verbruggen summarised the results of this cumbersome process thus: “Our way of statistical testing was that we took three specimens, threw the result of the one with the biggest difference away and took the average of the other two. Those figures were presented to the world. That was the way in which Delft dealt with statistics.” He meant that the lab tended to care more about the practical significance and implication of test results than about the statistical accuracy, which had to be only a means to an end.

Production of the first Arall wing panel at Fokker.

One of the sources of scatter was the production of the material. In those early years the Arall laminates themselves had to be produced in Delft, since ALCOA and 3M only delivered the ingredients: the aluminium and the adhesive. The aluminium had to be pre-treated, which meant cleaning, anodising and priming, before the laminate could be made in the laboratory by winding the fibres over the adhesive using a primitive lathe and then placing the outer aluminium layer on the fibres. The laminate was then cured

in the laboratory's small autoclave. Since there were not enough technicians in the lab and because the philosophy of Vogelesang and Schijve was to educate the students not only in a theoretical way but also with hands-on experience, these delicate processes were carried out by the students themselves. This was unique in a university. Verbruggen complained: "Pretreatment of the thin aluminium sheets in the small baths in the lab was not a fun job and sometimes was just skipped. No wonder that the quality was not always the same and that a lot of scatter was found in test results." The power of Delft was its speed. Whereas a test carried out by companies like Fokker and ALCOA would take months of preparation and paperwork before it could be done, an unsuccessful test on AraII in Delft in the morning could be followed by a modification during the afternoon and a successful test in the evening. What was more important, since the tests were fully carried out by the students, the test conditions could be continuously adapted, monitored and adjusted if necessary, whereas in industry and institutes the scientists define the tests while sitting at their desks and a half year later receive the results in the form of test data which they then use to write a report. Although both statistically and from the perspective of process control the Delft approach was not always 100% sound, this flexibility was a very important asset during the development of AraII and Glare.



Pretreatment baths in the Structures and Materials Laboratory.

Verbruggen's test results played a vital role as evidence in the case that was growing. He exposed many different kinds of specimens of the Arall material to a variety of hostile environments, including salt water and aggressive hydraulic fluids. He determined adhesion strength in all directions of a wide variety of different specimens, with names like Width Tapered Double Cantilever Beam Specimen, and End Notch Flexure Specimen, which were known to have different ways of failing if they cracked. Similar tests were performed on structural details such as joints. The effect of moisture and corrosion on the material properties of Arall appeared to be small. The epoxies did not crack, the lamina did not disbond, and the compression strength of the part did not cease to exist. Arall as it was contemporarily constructed withstood the most severe testing.

Lab culture

Verbruggen played an important role in the lab by motivating and guiding graduate students. Five to seven graduate students at a time would work on the material in the early days. In those days, approximately one hundred students enrolled the aerospace faculty each year, of which fifty would reach their final year. Less than ten would opt for the materials lab, with five joining the composites group and five the Arall group headed by Vogelesang. Sometimes a student worked under the direct supervision of Schijve on the more specialist topic of fatigue crack growth. The student room of the Arall group in the lab was named 'The Swamp' after the television series 'M*A*S*H', which was popular at that time. It reflected the kind of culture of 'can do' and the humour of the fictitious army doctors 'working' under primitive conditions in Korea. A tough competition of darts and chess was played between the students. The coffee table was the meeting place where the victories in darts, but also with Arall, were elaborately discussed. When student involvement began in the early 1980s a typical day in the Swamp would start with a gathering over coffee at 9 AM. Later, when the group grew, coffee time was spread over the whole day, with continuous discussions going on at the coffee table. When a new laboratory building had to be designed in 2000 to accommodate the growing staff, Boud Vogelesang insisted that it should be designed around the coffee table as a central meeting place, where staff and students could informally discuss

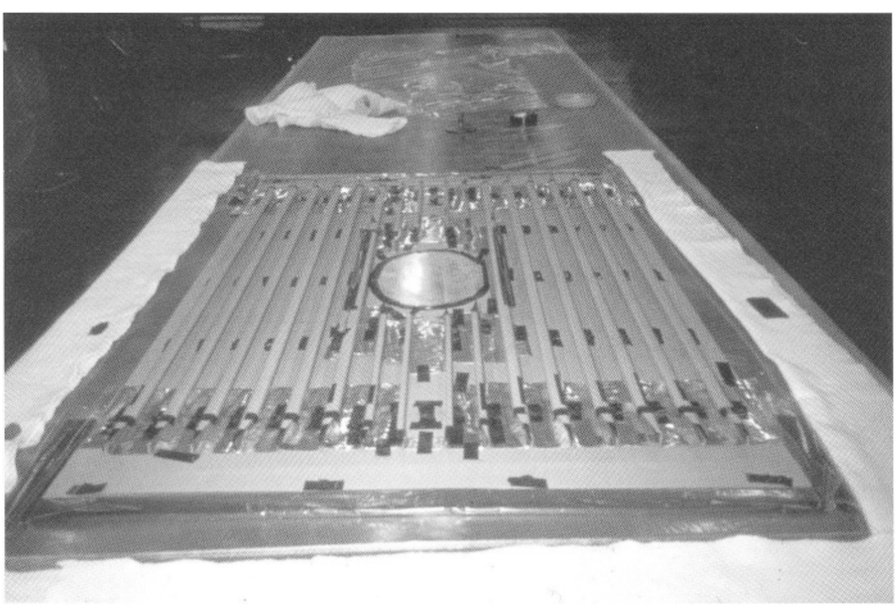
technical problems as well as the political situation in the world. The coffee table gives the work in the laboratory a very personal touch.

The 1982 annual report for STW listed seven undergraduate students and one PhD-student. These numbers grew to twenty-nine and five, respectively, in 1988. Many different aspects were covered. For example, the student Cees van Hengel modelled the behaviour of Arall in a tensile test in 1981 and Stein Pietersen studied an alternative for the stretching process after curing, a method for avoiding thermal stresses by fixing the various layers of Arall in the autoclave during the curing process in 1983. Back then, students were still full of ideals and formed a closely-knit group. The university environment had many of the characteristics of an ivory tower, and the corporate world largely remained beyond the horizon – a sorry contrast with the present situation, where students watch the stock market on the Internet and have already adopted the corporate mentality, with jobs waiting as soon as they graduate. Early Arall research was helped a lot by the typical atmosphere that prevailed in the lab: those involved felt a sense of competition with the outside world – a spirit of ‘us against them’. ‘Them’ could be the board of the university or Fokker or other aircraft manufacturers who were not clever enough to think about the validity of their standard test procedures for Arall. The growing worldwide interest in Arall created an atmosphere that made it seem as if the Delft laboratory was the centre of the world. Vogelesang frequently hosted important visitors who got a guided tour of the lab and were confronted with enthusiastic students sitting at their test machines. For the students, it was a thrilling experience to be at the centre of attention. They were considered to be project leaders, with corresponding responsibilities. Even though Arall ultimately failed, working on it provided an excellent playground for educating engineers.

One of the early students was Dong Chen, a brilliant Chinese student who had won a scholarship from his government. Dong got used to the capitalist system, never to return to his native country. Within half a year of his arrival in Delft, he managed to learn to speak Dutch fluently. He is still remembered at the coffee table for winning a bet by estimating the height of the Feyenoord soccer stadium in Rotterdam with an accuracy of one inch, just by taking the mathematical average of all previous bets. As a project leader, Dong was a special case. After his graduation in 1984 (cum laude) he stayed and started dissertation research on Arall, dropping the first objects on the material to investigate its so-called ‘impact properties’. Composites are notoriously sensitive to this kind of damage, and Arall did

not behave as well as aluminium. Later, Chen changed his subject to the behaviour of fibre-metal laminates in fuselage structures.

Obviously, Arall required lots of research – too much for some. One of those to leave was Verbruggen, who received his PhD in 1987. He was the last student who had to write his dissertation on an ordinary typewriter, and with a critical supervisor like Professor Schijve, this was definitely not an easy task. Several times he had to type his work anew before he received Schijve's approval. Verbruggen went to work on Arall at AKZO as a marketing and sales manager, first in Arnhem in the Netherlands and later in the United States. Verbruggen later quipped: "I found out that I was not a researcher" and even regretted his PhD-work in Delft. Verbruggen later returned to the Netherlands after AKZO had cutback its activities to its core business and even sold its fibre division, including aramid production and Verbruggen himself, to an investment company. The aramid branch was eventually sold to Teijin, a Japanese manufacturer of carbon fibres, Verbruggen's current employer.



Arall F-27 wing panel on the autoclave table.

Others persevered, including Vogelesang, who acted as the interface and ambassador between the lab and the outside world. He shielded both the staff and the students from financial and managerial problems and other disappointments and amplified positive news to create a stimulating environment. He secured materials and equipment for the students to perform their tests, and used his unique insight and his grasp of the scientific basis of the entire project to select and guide adequate research projects. While Schijve took care of the critical and scientific view of the work, Vogelesang motivated, gave perspective and highlighted their positive results. The two made a perfect team. In addition to receiving invitations from many companies and research institutes, Vogelesang was also instrumental in spreading graduation reports of the students from Delft around the globe. In 1983 alone he visited Airbus in Toulouse, ALCOA in Pittsburgh, NASA in Langley, the US Navy in Washington and the US Air Force in Dayton.

Although the contacts with the Fokker headquarters at Schiphol did not raise much official support within the company anymore, Delft's relationship with the Fokker site in Papendrecht, the former Aviolanda and the first location where metal aircraft were built in the Netherlands, remained good. The culture at the Papendrecht plant matched the no-nonsense, can-do atmosphere in Delft. This led to years of fruitful relationship. In 1981, students doing their practical training in Papendrecht started up manufacturing tests to establish Arall's workshop properties, such as how easy it was to cut and drill the material. Although similar potential was found for laminated aluminium in the 1950s and applied in the bulkhead of the F-27, as was mentioned in the first chapter, the excitement was enormous when Arall appeared to be able to undergo permanent bending deformations after curing, allowing more complicated products such as stringers to be created from flat Arall sheets by plastic deformation. This opened up a wider range of possible ways to apply the material. Cutting, drilling and riveting also appeared to be possible and actually proved to be a lot easier than for composites. The production machines in Papendrecht developed into a playground for students wishing to explore the limitations of Arall and gain shop-floor experience with this new material. This was a very important extension to the lab environment of Delft.

Structures group

We have already seen that 3M, ALCOA and AKZO were involved as material manufacturers in the Delft Arall project. These companies wanted to see some serious interest from aircraft manufacturers in order to justify continuing their efforts. For this reason, they visited aircraft producers accompanied by a representation from Delft. On such trips Boud Vogelesang would be accompanied by Jan Willem Gunnink of Delft's Structures and Design group. Gunnink was, like Vogelesang, an associate professor with the Faculty of Aerospace Engineering, but did not belong to Schijve's material group. He had graduated in 1977 and stayed in Delft as assistant to Professor ten Asbroek in the Structures group of the famous specialist on aircraft structural mechanics, Professor van der Neut, using his very theoretical work for the design of aircraft parts. The theoretical group of Van der Neut and his successor, Arbocz, had a different approach to research compared to that taken by the materials and production group of Vogelesang and Schijve. Gunnink's highly theoretical group was situated on the ninth floor and did not have a good relationship with Schijve's and Vogelesang's 'bicycle repair' group in the lab downstairs. They considered the reports of this group to be 'unscientific' and disparagingly called them 'sheets from Schijve'. This is somewhat surprising, since the international scientific community acknowledged the group to be world leaders in their field. The difference in opinion was part of the academic debate and did not really hamper the personal relationships, and the groups worked well together throughout.

Gunnink became involved in the Arall project in 1979 when two students, Kees Venselaar and John Heijdra, came to him wanting to do design studies on the new material for their thesis work. Gunnink met with Vogelesang and together they became the main thrust behind the Arall and the later Glare projects. They were called the 'Siamese twins' and a deep friendship grew, also because of their common Christian world view and their strong involvement in their respective church communities. It was in the course of this co-operation that Vogelesang and Gunnink managed to integrate their respective labs into a single Structures and Materials Laboratory, which was opened officially in 1991. The structures group had developed a test facility on buckling under compression and on temperature loads on structures, but this group was usually described by the materials people as those who perform calculations without confirming whether the

outcome is correct by testing. At the same time, the structures group saw the materials people as the ones that test without thinking. Merging the two in one lab was certainly an achievement and a challenge for both cultures.

Gunnink's co-operation proved essential because, at the end of the day, the aircraft manufacturers would have to be able to design aircraft structures with the new material. The material alone is nothing. In 1983, an Arall working group was formed in the Netherlands with participants from Delft, Fokker, NLR and NIVR. Fokker was asked, especially by the NIVR, to play a more active role in the area of Arall applications. Discussions started with ALCOA based on the work of Gunnink's students on the F-27 and in particular the manhole used for inspection of the inside of the wing just outside the engine area. Fokker decided that it now wanted to become involved in the project, announcing that it planned to initiate discussions with ALCOA to advise them on the right bonding process they had to apply for Arall. Fokker also initiated design studies to get an idea of the possible weight savings and related costs. Gunnink's students had already studied the application of Arall for the wing of the F-27. One of the features they discovered by computer simulation was that the surrounding of the manhole to which the cover is bolted is crucial. This area has to be reinforced, but this reinforcement in turn attracts more loads, making the area even more critical. One of the solutions was to make this area less stiff by laying the fibres in the material in another direction. Arall offered new opportunities to tailor the material and Gunnink's work opened the way to take advantage of them.

Production

As we already discussed in the first chapter, the wing is a very fatigue significant structure and a lot of test and analysis work had already been done on aluminium wings. The oldest F-27 aircraft were reaching the end of their design life, and Fokker did a lot of test work on a critical detail of the wing, a panel with a tank inspection hatch. The results of this life-extension programme made it possible to fly the F-27 beyond the originally intended design life. Since much was known about it, this wing was a perfect playground with which to study the application of Arall. Gunnink was starting to do a lot of design work on an F-27 wing panel made from Arall and Fokker wanted his help for this.

First large Arall production panel made by ALCOA (upper) and first Glare production panel for the A330/A340 barrel test in Hamburg manufactured for SLC at Fokker (lower).

Fokker, Delft and ALCOA met in 1984 to discuss the possibilities of the design and testing of a part of the wing of the F-27 made from Arall. ALCOA committed itself to produce the required panels of 2 metres long and 1.5 metres wide. Up to that moment it had only produced tiny panels of roughly A4-size.

ALCOA considered the material a valuable response to the composites that were beginning to threaten the business of aluminium, and wanted to sell the material as a semi-finished product, in the form of sheet material similar to the aluminium sheets they were accustomed to. They would, of course, also produce the material. During approximately the first five years after Arall's birth, ALCOA would be Delft's prime partner. At that moment the questions around the patents were still not completely resolved and it was therefore uncertain how strong Fokker's position would be regarding ALCOA if it wanted to use Arall for the F-27. The company stressed that it counted on the promise by Delft that the patent would not harm Fokker.

In 1982/83 the first commercial product under the trade name Arall – a name invented by Vogelesang – was launched by ALCOA. The grades Arall-1 and Arall-2 were standardised. Arall-1 was a variant with aluminium 7075 layers and was stretched after curing, and Arall-2 had aluminium 2024 layers and was in an as cured condition. Of the fibre/adhesive layers, 41% of the weight consisted of aramid fibres. The production started in 1984 and the official introduction took place at the Paris Air Show in 1985. Later, in 1987, two other grades, Arall-3 (7475 aluminium, identical to Arall-1) and Arall–4 (with a different, high temperature adhesive for military applications) were also standardised. The panels produced had a size of 8 feet by 4 feet. A production plant was set up to manufacture 1 million square feet per year. Due to the various treatments the material had to undergo in its production, the price of Arall was high: of the order of ten times that of aluminium per kilogram. In Europe the chromic acid anodising process for the aluminium layers was chosen, whereas in the U.S. the more environment-friendly process which used phosphoric acid anodising was applied. Cladding (adding a pure aluminium layer on the outside) was possible for customers that preferred a polished, shiny outside skin for their aircraft.

The pretreatment, layup and curing for Arall was performed in building G at ALCOA Technical Center near Pittsburgh. This windowless, top secret building was erected by ALCOA to produce composites for defence applications, but they never actually received a contract. Because the

ALCOA division itself was set up in New Kensington, Pennsylvania, the crew would travel to the ALCOA Technical Center to produce the laminates. Only the ultrasonic inspection of the produced laminates was done in New Kensington itself. The New Kensington plant was led by Bill Evancho, who took the position because he was bored with his previous job for ALCOA. He persuaded ALCOA'S Board of Directors to invest $20 million in the production of Arall. The crew was very dedicated and eager, and according to a description of the atmosphere in *The Wall Street Journal* it was not unlike the culture in Delft, with even the coffee table present:

> "At their trailer offices, neckties are optional. When employees take a cup of coffee, they are asked to contribute coins to the coffee fund. They put in long hours at the factory, which looks like a sparse, open hanger. The machinery itself looks as it came from a rummage sale: State-of-the-art control panels operate 1940 heavy machinery. (...) In this battered old factory town lives a rare breed of moguls. They work out of a trailer. They have power lunches at Eat 'n' Park. Their machines predate World War II. They type their own letters, and clean up after themselves. Their company? ALCOA – the world's largest aluminum producer. Aluminum Co. of America hopes that by freeing these workers from the shackles of bureaucracy (and the lap of luxury), and by letting them work in their own small unit, it will tap the entrepreneurial spirit... Studies suggest that such ventures fail most often because they lack autonomy and separate facilities or get otherwise tangled in the bureaucracy of their corporate parents... The technology is brand new, giving the Arall makers a more authentic start-up feeling."

To *The Wall Street Journal,* ALCOA vice president Sandy Nelson stressed: "The interference of other products would diminish the emphasis on Arall. But that is not a problem for Arall's current makers. They're a highly energetic team with a very narrow focus. That is a very powerful combination."[1]

[1] *The Wall Street Journal,* August 1, 1990.

Wing panel

To incorporate Arall into the design and construction of an actual aircraft, Fokker was the obvious candidate as far as the Delft group was concerned. However, Fokker's problem in applying Arall was that after the F-27 in the mid-1950s, and the F-28 at the end of the 1960s, no new aircraft types had been developed. For the application of Arall, this meant that the extra costs of changing an existing structure had to be overcome, which would counterbalance the operational cost savings obtained from a lighter structure with a new material. The application of Arall, and later Glare, would therefore only make sense within the context of the development of a completely new aircraft. For years Delft had to keep the material alive, waiting for a window of opportunity through which it could penetrate a new aircraft design. At Airbus and Boeing, similar problems were encountered. The leading aircraft producers were building derivatives from derivatives. At the time of Anthony Fokker, a new aircraft was built almost every month and the application of new ideas was certainly a lot easier. The product cycle in the 1980s was now of the order of decades and the aircraft industry had become far more conservative and reluctant to apply new technologies since the financial risks had also increased significantly.

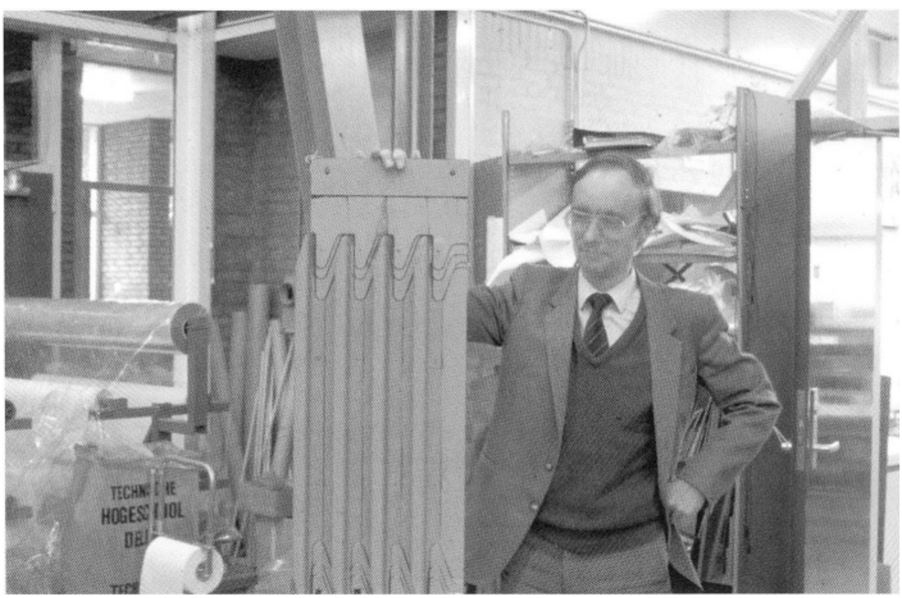
However, finally in 1984 the Delft community held its breath. Fokker was considering a completely new aircraft to follow the F-27 and F-28. At that moment, updated versions of the F-27 and F-28 were being developed, the Fokker 50 and Fokker 100, but these aircraft were still quite conventional, although they imposed a very heavy workload and financial burden on the small Fokker company. The time was ripe for this small company to co-operate with the European industry in the Airbus consortium, but the drive and pride to remain 'self-creative' remained strong in every vision the company produced. Fokker wanted to design and built its own aircraft. Obscured by the work on the Fokker 50 and Fokker 100, the design bureau envisioned the F-XX as its new target. The company presented a materials technology plan for this aircraft, which aimed at including an ambitious number of new technologies. The background for the new project had certain similarities with the situation in the days of the development of the F-27, and indeed this success story was recalled. It was planned that composites would make up about 50% of the structure of the F-XX, compared to a mere 5% in the Fokker 50 and Fokker 100. In the F-27 glass fibre composites were only applied for the secondary, non load-carrying

structure, but in the F-XX composites would be used throughout the structure. This was striking, because composites were still subject to strong controversy in the aircraft industry at that time. It was also surprising that the less revolutionary concept of Arall was not considered to be viable for this new aircraft. The F-XX would entail a heavy development load for the company, especially considering the fact that composites were primarily concentrated in two of its plants (Hoogeveen and Ypenburg) whereas the remainder of Fokker was only capable of manufacturing metal parts and were also scattered over four different locations (Schiphol, Dordrecht, Papendrecht and Woensdrecht). Fokker had put Arall 'in the refrigerator', and this message, coming as it did from one of the partners in the development of the material, was certainly a major blow for Delft.

Fortunately for Delft, the NIVR stepped in to fund further research on Arall. The work that had been started in Delft on the F-27 wing panels could now be fully executed. The wing was the natural place to apply Arall since this was already a bonded, laminated structure in the F-27, and because it was also very fatigue critical. Two Arall wing panels would finally be built and tested. Also flying demonstrators, i.e. tank covers, were designed, manufactured and mounted by Fokker to fly on F-27s. The F-27 wing panel project received official approval in 1984 and was started in November 1985, the same period in which Fokker decided *not* to use Arall in their new F-XX design. Up till then, many small specimens had been tested in Delft, creating a basic confidence in Arall among the different partners, but it was now time to study a realistic aircraft component. For the small group in the Delft laboratory, this was *the* moment, comparable to Schliekelmann's step when he received his grant from Van der Maas to build a bonded S-11 wing.

The dimensions of the panel would be approximately two by one metres and it would contain one access hole, used in service for internal inspection of the wing. The same loading would be applied as for the aluminium panel, and because the Arall was lighter and thinner, the mean stress level in Arall (mean stress in flight) would be 86 to 100 MPa, whereas the stress in the aluminium panel had been 77 MPa. The target to be achieved was a weight reduction of 25%. The work packages for this F-27 wing panel project were portioned out and the different details of the large panel would be tested separately before the whole panel was made. Delft (Gunnink) would do the design work and make the production drawings, and therefore NIVR granted Delft research funding – the first time NIVR had done so since its foundation in 1947. With the money, Delft was able to buy

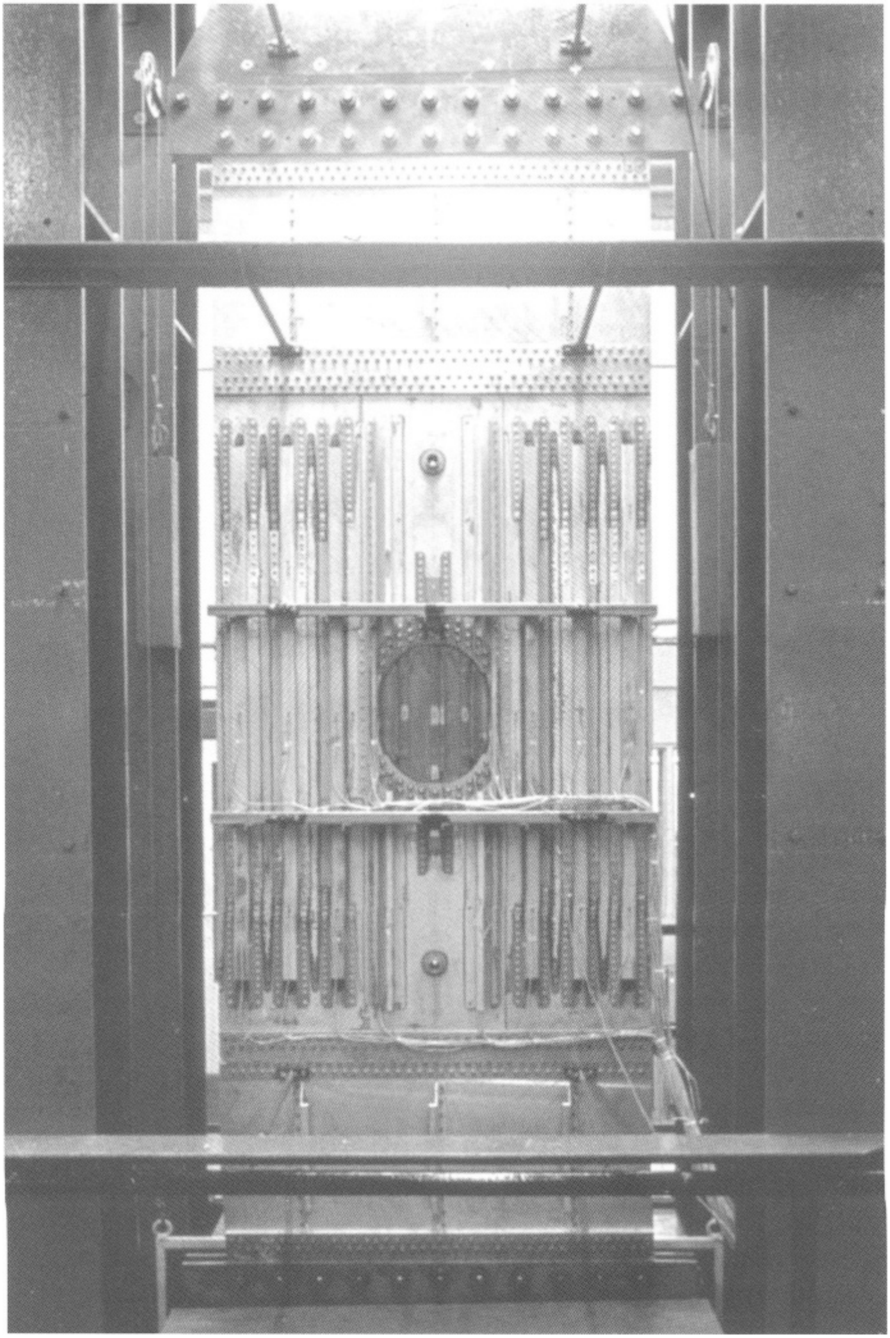
a computer to make the design and the drawings. Unfortunately, Delft forgot to include Value Added Tax in the requested money and therefore found it had to contribute involuntarily to this very expensive equipment. Gunnink had the difficult task of developing new design methods, as there were none available for Arall at that time. For example, for a compression analysis, 32 pages of mathematical formulae based on Van der Neut's method had to be derived for Arall, checked and implemented in a computer program. With this program, the buckling load for the Arall panel could be calculated. Delft would also execute the detailed tests, whereas Fokker was to carry the prime responsibility for the production and assembly of the Arall parts and for the testing of the large panel. Due to the urgent Fokker 50 and 100 projects, the company stated that it was unclear at that moment whether Fokker could meet these obligations. The overall responsibility would be carried by Delft. The tests were set up as Fokker's support for the Delft wing project.



Boud Vogelesang with an Arall detail specimen (end fitting panel) manufactured and tested in Delft for the F-27 wing panel project.

During the course of this, I was hired as an undergraduate student by Fokker Papendrecht in March 1985 to assist Fokker with the research necessary for the production of parts of the wing panel. The production of the various Arall parts was planned to take place in the Papendrecht plant. I had already spent a period of practical training at Fokker in August 1984. Just before me, another student, Geert Roebroeks, had started his practical training at Fokker Papendrecht and had studied the milling process for Arall. Roebroeks and I would remain involved in the Arall and Glare projects and our practical experience at Papendrecht certainly bore fruit. Like Roebroeks, I had to sign a secrecy agreement that prohibited the publication of the results – a fact that would later play a role in our story.

In 1986, detailed tests for the wing panel were running in Delft and, although there were some minor problems, the project was running rather smoothly from a technical point of view. From these detailed tests it became evident that Arall was quite sensitive to strength reductions caused by holes drilled in the material (so-called 'blunt notch strength') and that, while the material had excellent fatigue crack growth properties, thickness steps (doublers bonded on the structure to increase strength) were susceptible to premature fatigue cracks. In particular, bending of the material at these locations caused cracks to grow at the outside layer of the laminates since the fibres are less effective during this type of loading by bending. The studies Roebroeks and I did on the production aspects at Papendrecht were successful. The production of parts did not create special problems relative to aluminium. The large wing panel was assembled from these parts and subjected to three times the design life of the F-27, i.e. 270,000 flights. Only minor cracks occurred at the fingertips, i.e. the thickness steps of the doublers, and these were only in the outer layer of the Arall. This meant only a minor surface scratch in Arall whereas the aluminium equivalent would have failed dramatically. The damage tolerance properties of the Arall structure proved to be excellent and something like the Comet accidents would never need to happen again. Fatigue could now be considered conquered. The residual strength in a cracked condition was high. On top of this increased safety level a weight saving of 33% compared to the original design in aluminium was achieved. The blunt notch strength appeared to be critical, but the wing panel was a big success. Together with the durability results of Verbruggen, this test on a realistic full-scale panel would convince all the potential users of Arall. It certainly made *a* strong case.



An F-27 wing panel in a test machine at Fokker.

Struggle

Then, surprisingly, NLR and Fokker started negotiations in 1986 about the research into Arall to explore how NLR could be more involved in the Arall work, which was concentrated in Delft at the time. The purpose of these meetings was even to determine whether there would be a role for Delft next to that of NLR in the new Arall projects to come; studies concerning the application of the material in fuselages, for example. The feeling was that Delft had played its role in initiating the idea, but that it was now time for Fokker and NLR to take the lead in commercialising the material. Delft was informed about this and was obviously furious because the only way to survive as a university research group was by doing contract work. The feeling was that Fokker had 'hijacked' the Arall project for the F-27 wing panel, and the idea that Fokker now imagined it could decide whether there was still a role for the university seemed ridiculous from the Delft perspective. This turn of events contributed to Delft's refusal to sign the secrecy agreement that Fokker wanted to put in place to cover the F-27 wing panel project. Although it was recognised that it would be reasonable for Fokker to try and control the flow of information from the perspective of the company's business interests, Delft's strategy was that to convince the aviation community, it had to be confronted with all the evidence that was available in an open way.

This 'noble strategy' was never easy. In 1986 the fight with Boeing on the basic patents was still open. On the very last day possible, on the 4th of September 1986, Boeing had launched another attack based on its published results and the early Fokker results. One day, Delft was even visited by somebody who tried to obtain Marissen's Master's thesis report from the university library, to check whether this was open literature in order to attack the patent. In the library this man found out that this was not the case and that he had to contact Vogelesang. He went to him, only to be told that this work was restricted. However, in the end all the various attacks on the Arall patents were in vain.

Although technically the F-27 wing panel tests ran relatively smoothly and proved the excellent properties of Arall for the first time on a realistic structure, the co-operation between Delft and Fokker saw an increasing number of difficulties, both on the institutional level and on a personal level. In a way this was tragic, especially since the project drew a lot of attention from aircraft specialists all over the world. As the success of the wing panel

project became apparent, Delft started to feel pushed aside by Fokker. It was no longer simply a fight between Delft and Fokker, but also a quarrel between ambitious project leaders within the Fokker company and Delft researchers who felt that Arall was their work and that they should therefore receive the credit. The divergence of interests was particularly sad because both parties needed each other to survive. Delft remained committed to the only aircraft industry in the Netherlands, while the Fokker project leaders were educated in Delft and needed the university's capabilities to solve their problems and to hire new engineers. Underlying the controversies lay the fact that the enhanced reputation of Delft and the group's wide recognition outside the country was not reflected in a more symmetrical relation of mutual respect with Fokker. The quarrel was transferred from the working level to the higher management levels, but was not resolved. Probably a sensible discussion could have resulted in a solution in which Delft could get the credit and Fokker the benefits of this material; the Arall project had all the makings for the creation of a win-win situation. However, the problems were not solved but became more entrenched. The controversy became emotional, developing all the characteristics of a chess game in which the partners observed every move made by the adversary with suspicion. Delft felt it was not taken seriously as a research institute that could be of benefit to Fokker. The respective cultures were also different. The can-do, pragmatical approach of Delft collided with the hierarchical and formal way in which Fokker worked. The lab in Delft was named the 'bicycle repair shop' by Fokker employees, a name that the scientists in Delft accepted with a mixture of pride and ill will. Next to the Wright brothers, they were surely not in bad company. Fokker was evidently not used to the new situation in which Delft had to earn its own research money, to which Fokker never contributed. Fokker's view was that Delft had played a role, even an important one, but that a shift would occur now from research to commercial aspects and that it logically followed that Delft's role was over. Arall had to wear the name of Fokker. After the years of research that had gone into Arall, this was unacceptable to the university, and in response Delft even considered ending its co-operation with Fokker. Most remarkable is that at the same time all the people involved in the project remained on speaking terms and remained co-operative. Fokker and Delft never divorced.

The chess game was played around presentations on the results of the F-27 wing panel tests at conferences. As at the beginning of the fibre-reinforced metal laminate work, Delft's role was sometimes not

acknowledged in Fokker presentations at international conferences. This time the reverse was also claimed to be true. The game was also played around a video produced by ALCOA for marketing purposes, in which the birth of Arall and the shared work on the F-27 wing panel project was not addressed in a way that satisfied Delft. This chess game absorbed a lot of precious time and energy.

The first Arall conferene

The relationship reached its lowest point just as a big international triumph was to be celebrated. In October 1987, the luxurious ski-resort of Seven Springs, set against the backdrop of the beautiful colours of an ‘Indian Summer’ in the forests around Pittsburgh, was the location for the first international conference on Arall. Boeing, Douglas, Lockheed, British Aerospace and De Havilland Canada were all doing small test series on the material. Samples of laboratory-fabricated Arall-1 were sent in 1985 and 1986 to more than thirty aerospace companies and government agencies, which committed to assist in its development. However, Fokker and Delft were far ahead of their competitors. The work on the F-27 panel showed that although small cracks could occur early in the life of an Arall structure, these tiny cracks would only grow very slowly. The first discussions were held on the relevance of those small cracks in the light of regulations that forbade airlines to continue to fly aircraft in which cracks have been identified. For Arall this would be a big disadvantage, preventing the use of the material to its full potential. Inspection and repair would be as frequent as for aluminium. At the conference, the Americans expressed doubts about bonding. Boeing had done some bonding in the past, but not to the high standards that Fokker used. This had led to disbonding in service, which was exemplified in the Boeing 737. This aircraft had bonded fuselage panels that were found to disbond and delaminate during service. Arall performed perfectly in the experience of Fokker and other European manufacturers, but the American producers maintained their reservations about the material. This remained a problem during the whole Arall and Glare project.

Nonetheless, Seven Springs was a very successful conference. It was organised by ALCOA, by people with the typical American-style enthusiasm and humour, including Mike Gregory, Larry Mueller and Bob Bucci. After my graduation in 1986, I was hired by Vogelesang on the STW

Attendees of the first Arall conference in Seven Springs.

Attendees of the first Arall conference in Seven Springs (continued).

project as Verbruggen's successor to produce a dissertation on the properties of the material under impact, a critical aspect for composites and probably also for Arall as Dong Chen had shown.

I still remember vividly how the Delft delegation – Vogelesang, Schijve, Gunnink, Roebroeks, Verbruggen (as an AKZO employee) and I – flew business class in a good mood on the upper deck of a Boeing 747 to this milestone in the Arall project. It was my very first trip. Finally, after years of dedicated work, we felt that the end was near. Arall would soon be used by all those manufacturers who were interested, and we would be part of it. I would show my first research results at the conference. Roebroeks had built a drop weight tester that I had used to drop steel objects on aluminium, Arall and composite sheets to determine the resistance against accidental damage. The steel objects were intended to simulate objects like dropped tools during maintenance of the aircraft, or stones thrown up from the runway hitting the structure. Although the first results revealed that Arall was sensitive to this kind of damage compared to aluminium, composites proved to be even worse. And after damage the fatigue resistance of Arall was much better than that of aluminium.

We were well prepared. I would deliver my first speech at an international conference and had practised it dozens of times at home with the mirror as audience. To show the world what kind of work had been done on Arall in Delft, we had printed a booklet with a poster presentation on one of the student projects on each page. Many students in Delft had assisted in producing this booklet. To make the case, all relevant aspects of the material were covered to some extent and it really looked impressive as evidence. Obviously, we wanted it to convince the 'jury of the aviation community' that a lot of data was available, and that Arall was an interesting material different from aluminium and composites. However, on the day of arrival the booklet outlining the student projects became the subject of the next quarrel. Two of the posters contained work done in Papendrecht, one of which showed work done during my practical training and Master's thesis work for the F-27 wing panel project. It was work that was covered by the secrecy agreement that I had signed on my first day at the Fokker plant. Therefore Fokker, careful not to let 'their' secrets out, forbade us to distribute the books. We found a very practical response to this new position on the chessboard. I still can picture the whole Delft delegation sitting in Schijve's hotel room in the middle of the night – Schijve in his pyjamas – tearing out the page with my contribution book by book. The next day we distributed the booklet to the conference

participants as if nothing had happened. Technically, the rest of the conference was a big success. Many aircraft producers showed interest in Arall, and ALCOA did an excellent job in marketing the new material. But behind the scenes there was much ado about nothing.

There actually was a second fight at the Seven Springs conference, and this had more of a technical content. Marissen was almost ready with his PhD-thesis at the DLR in Germany. In the meantime, Roebroeks had started his PhD-work in Delft and he had some overlap with Marissen's subject. Marissen kept contact with Delft to get the materials he needed for his research on the modelling of fatigue crack growth in Arall, but for the most part he worked in Germany, more or less in isolation. Officially, Marissen was one of the inventors of Arall, but the close contact was lost.

End of Arall

Almost at the same time, Roebroeks and Marissen both discovered a detrimental property of the material that would finally be the end of Arall, although not of fibre-metal laminates as a family. Up to that time, research had concentrated on wing applications and this culminated in the successful F-27 wing panel project. This concentration on the wing had a historical explanation, as we saw earlier. However, MBB in Hamburg had also started to become involved in the material and for them the fuselage would be a more likely application. Against this background, tests for the application of Arall for the construction of aircraft fuselages had shown that under loading conditions that resemble those of the fuselage of an aircraft, the aramid fibres around a fatigue crack would break. With the aramid broken, crack growth would no longer be slowed down. Of course this was a very serious issue, since without intact fibres the whole concept of Arall would not work. The person to uncover the bad news was the only Delft University student to work for Marissen at DLR: Johannes Homan, who graduated in 1984. It had been Homan's task to study the behaviour of Arall at low load frequencies. Usually such tests are accelerated in the lab. The inflation of the fuselage which is done every flight and usually takes more than an hour, is performed ten to fifteen times per second in the lab in a fatigue machine (a frequency of ten to fifteen Hertz). For aluminium this is a normal procedure. For Arall this was also carried out, although it was not clear whether a high frequency would produce the same results as a realistic one. Homan had the task of

finding out, and he discovered that fibre failure did in fact occur at a lower test frequency. Marissen and Homan thought that the adhesive would have time to creep at low frequencies and moreover the adhesive would deform permanently, which would prevent the fibres from moving away from the bridged crack when the crack closed. When the crack closed, the fibres would therefore be crushed and come under compression. It was already known that aramid fibres behave badly under compression. Although aramid fibre is much stronger than steel, research showed it could be damaged and would finally break under low compressive loads. The slipping phenomenon due to creep followed by compression was therefore the explanation of Marissen and Homan. Roebroeks had a different explanation. He thought that the aramid fibres had very little connection with the adhesive. The aramid fibres lay loose in a tube in the adhesive and when pulled out they therefore slipped out of the tube without deformation of the adhesive. When this was followed by compression, the aramid fibres behaved weakly under compression and would be damaged and break. The difference between both explanations is small and not terribly relevant from a practical standpoint. From a scientific point of view, a definitive answer was never given. Marissen's model showed that adhesive deforms permanently, whereas Roebroeks' indicated that the aramid fibres had no cohesion with the adhesive and slipped out.

From a technical standpoint this already presented a hazardous situation, but what made the discovery *really* tricky was that there was no uniform explanation for this phenomenon. How to explain this, with the whole aircraft manufacturing community present in Seven Springs? What was needed was a really good, convincing and reassuring story. However in this case two scientists from Delft stood opposite to each other, and certainly Marissen wanted to score a point since he was after a kind of revenge. Besides, Marissen was also not on speaking terms with Fokker because one of his publications had been cited without mentioning his name. The Seven Springs gathering had enough technical and institutional fireworks to kill Arall in front of the entire international aviation community. Nonetheless, Arall remained alive in Seven Springs. Delft had sold its refrigerator again, with Fokker at its side. The results for the F-27 wing panels proved Arall's excellent properties for wing applications. Although Marissen and Roebroeks fought their battle between the lines, it was stated clearly by both that failure of the fibre could only happen for loading conditions similar to that of a fuselage. Moreover, Arall that had been stretched after curing did not show

this phenomenon. A cheap method to induce stretching, a roll forming process, was being studied by one of the four PhD-candidates at Delft at the time: the Chinese student Dong Chen. Fibre failure could therefore be avoided or resolved.

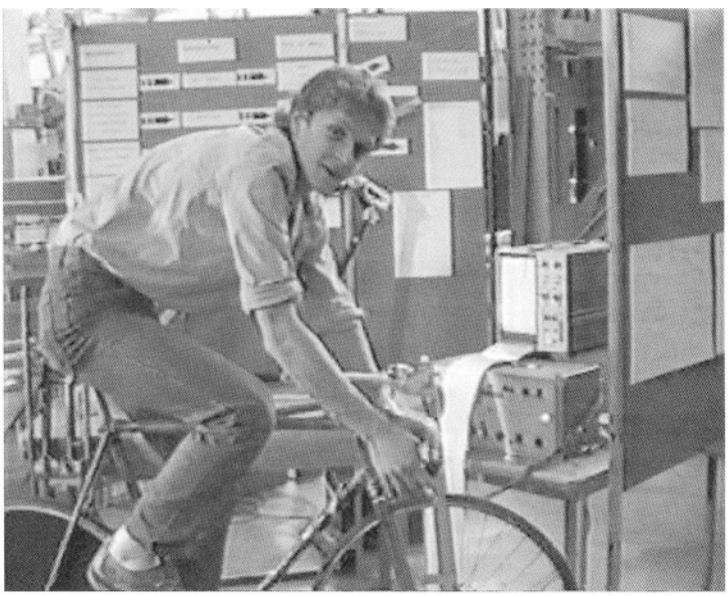
However, controversy or not, the Arall development did not stop there. Already a new variant was being developed in Delft that did not show the fibre failure behaviour at all: a version of Arall with glass fibres developed by Roebroeks and Vogelesang. Glass fibres were nothing new. Indeed, De Bruijne had already studied the application of glass fibres in composites and they had been applied in the F-27. Nevertheless, the relatively sudden change of course in the development activities in Delft, away from aramid and towards glass fibre, presented a tricky situation: ALCOA was introducing its first commercial Arall products based on aramid fibres. Now Delft had come up with a new material: a laminate with glass fibres. Almost nothing was known about this new variant. It meant that all the evidence that had been gathered so far could be thrown away.

New variants

Apart from the variant with glass fibres, Delft also developed several other new types of Arall. In 1986, a patent was filed on a special variant of Arall intended for use as armour plating, with Vogelesang, Paalvast and Verbruggen as inventors. This type of Arall had ceramic tiles on the outside to break up a bullet hitting the material, whereas the Arall backing layer would absorb the remainder of its kinetic energy and would in this way stop the bullet. Early tests were done in Belgium, where Verbruggen came from, in his parents' backyard, since his father owned an impressive collection of weapons. In the same year, government support was obtained to develop new armour based on Arall under the name 'ballistic Arall'. Aramid fibres were widely used in armoured material at the time and it was felt that ballistic material would be superior. However, I had already shown that Arall is sensitive to impact loading and after an extensive test programme carried out by the Dutch military and TNO, it was concluded that the material was not viable.

Other developments turned out to have more potential. In 1988, the undergraduate Coen Vermeeren tried to come up with an Arall type which would be able to withstand the high temperatures occurring in space

structures and supersonic transports: an Arall with carbon instead of aramid fibres and titanium instead of aluminium layers. The carbon fibre was manufactured by Teijin, the Japanese company that would later buy the aramid manufacturing plant of AKZO. The possibilities of Arall with its different components seemed to be endless, and even more new variants were introduced and tested. A patent was filed on Vermeeren's variant and this supplied enough research topics for new generations of students for years to come. In the same year, a patent was filed on a manufacturing process for Arall tubes with Harald Bersee and Vogelesang as inventors. The tubes were promising for applications in the chemical and nuclear industry because they remain leak-proof even if damaged.



Technician Kees Paalvast riding an Arall bike to measure stresses.

The same patent covered a bicycle made of the tubes and contacts were established with Dutch bicycle manufacturers. In this case, the bicycle repairmen from Delft could really live up to their reputation! In the same period, an Arall tennis racket which was ten percent lighter than a conventional racket was designed and made. However, the work on sporting goods did not improve the scientific reputation that the lab had within the Faculty of Aerospace Engineering. As explained earlier, Gunnink's structures group and other research groups within the faculty all considered the

materials lab to be inferior and unscientific, saying a tennis racket was a non-flying object. Still, all these ‘spin-offs’ added to the success story of the Arall concept within the industrial community and also within governmental circles. In 1987, a further patent on Arall with a thermoplastic adhesive was filed, mentioning Vogelesang, Meijers and Van Velze as inventors. This material would become soft at high temperatures and therefore was easier to deform than the original Arall.

After testing the first F-27 wing panel, the work at Fokker slowed down considerably. It took years before the second (Arall-1 instead of Arall-2) panel was tested. In a sense this was a lucky coincidence, since the second panel proved to be less successful than the first one and did not lead to convincing publications. The first flying Arall part would be a number of wing hatches for a Fokker 50 which was given certification by the Dutch airworthiness authorities RLD. For that reason it was also an important milestone. Other compression test panels and wing spars were designed and tested by Fokker without the assistance of the Delft group, along with a design study for a complete Fokker 50 wing box. Fokker was close to an actual application and Fokker therefore negotiated with Delft and AKZO at the beginning of 1988 for the rights to make Arall for special purposes itself without having to rely on ALCOA production.

The first application of Arall

At that time, Arall also began to gain international momentum and was about to take off. In 1988, one year after the conference in Seven Springs, a second conference was held in Delft.

At this conference, the French company Aerospatiale presented their study on a fuselage shell for an Airbus A320. However, the results were disappointing. Arall was clearly not suited for fuselages. The US Air Force was looking at top parts (dorsal covers) for their T-38 jet trainers to replace magnesium covers, which suffered from serious fatigue problems. A lot of marketing effort was put into this dorsal cover by Bill Evancho’s group at ALCOA. In October of the same year, the first commercial application of Arall was achieved by the ALCOA marketing people on the C-17 military transport aircraft. This aircraft suffered from heavy weight problems towards its rear, and therefore the large cargo door situated there would be manufactured from Arall by McDonnell Douglas.

Presentation at the second Arall conference in Delft.

Schijve in a debate at the second Arall conference in Delft.

Attendees of the second Arall conference in Delft.

The Wall Street Journal described this victory as follows: “The guys in the Arall programme are more aggressive than the run-of-the-mill metallurgists at ALCOA”, says Richard Pettit, an engineer at McDonnell Douglas, which agreed to use Arall in the cargo door of its C-17. “They got their material used on an airplane much faster than usual.” As this quote shows, the introduction of this new aircraft material was even considered to be rapid. Several other locations where Arall could be used on this new aircraft, such as the wing and the fuselage, were studied – also in Delft. Only the cargo door, with dimensions of 5.6 x 9.7 metres was successful. It was manufactured from Arall-3 and led to 26% weight savings. However, it also turned out to be a highly complex product when manufactured from Arall: stretch forming, roll forming, routing, bonding and riveting of many different components were necessary. The Arall panels that could be produced by ALCOA were too small and had to be connected together with expensive titanium straps. This clearly revealed the great Achilles’ heel of Arall: per kilogram the laminate was already about eight to ten times as expensive as aluminium. With the complex production steps that were necessary, this cost factor became even worse. Only about thirty C-17s were built with Arall

cargo doors. The weight reduction efforts for this aircraft were soon followed by a cost reduction round. Arall ‘fell off’ the aircraft just after take-off. However, this is part of the story of the rise and fall of Arall in the U.S., which will be told in the next chapter.

C-17 military transport aircraft.

First Arall cargo door installed on the C-17, February 27, 1991.

3

Toward Glare, fuselages and the U.S. (1988-1997)

Roebroeks

"I got the habit of a continuous building project on my house from my father", said Geert Roebroeks, when he gave me a tour of his premises. His house is situated at the side of a dike, near Den Bommel, a tiny village in the south-west of the Netherlands, on one of the islands of the province Zuid-Holland. It is an old house with a wide view over the polders, but in a continuous state of renovation. Roebroeks has been used to this since he was a boy, because during his whole life his father has done the same. One of Roebroeks' most recently started projects is the construction of a swimming pool in his garden. When it is eventually finished, the plan is to build a foldable, aluminium covering for it. It is one of the many never-ending projects on the premises. His former Delft colleague and roommate, Leo Meijers, was his neighbour for a long time, but in the end could no longer keep up the fight against degradation and the struggle to modernise a centuries old house. From the time when as a student he was continuously

tinkering with his Citroën Deux Cheveaux, such struggles have become a way of life for Roebroeks. He still owns one, which is under constant maintenance in one of his sheds. A restless person in a creative but not stressful manner, Roebroeks has a reputation for finding practical solutions quickly. This is reflected in his speech, for he speaks very rapidly, even in English. For this reason, some engineers at the German aircraft manufacturer DASA – now renamed EADS – preferred to call Gunnink instead of Roebroeks, since they could not keep up with his speaking pace and his quick train of thought.

Roebroeks commutes daily in the rush hour between his old, charming house in the polder and the colourful, high tech aerospace faculty building in the '*Randstad*', the busiest part of the country. Like many others in the Glare project, he has maintained his ties to Delft for a large part of his life. He did the work for his Master's thesis in the lab in Delft in the composites group, studying the adhesion between aramid fibres and the epoxy plastic of the composite, a weak point. This fibre is difficult to bond chemically to another material, which is exactly what has to be done in a composite if it is to function properly. Another weak point of the fibre is that it can easily be split into separate small fibres, so-called 'fibrils'. Roebroeks used this latter characteristic of aramid to combat the former. He invented a process to roughen the fibre in such a way that small fibrils appeared on the surface of the fibre. These small 'branches' improved the adhesion between the epoxy and the fibre. The epoxy was effectively entangled in the branches of the fibres, establishing a firm connection. This was a major step forward for aramid fibre in its competition with the much more successful carbon fibre. For composites, three main fibre types are used, i.e. glass, aramid and carbon, of which carbon is the stiffest and strongest fibre. In composites, aramid found it hard to compete against carbon. The fibre did not behave well under compressive loads, splitting easily under such conditions. Moreover, the aramid absorbed moisture and was sensitive to environmental degradation. In the cellar of the laboratory in Delft, Roebroeks built a big machine with his own hands, using rough stones that scoured the fibres and produced surface fibrils. In the lab he worked in the same spirit that he would later show with respect to his house. The aramid producer AKZO was at the time in the midst of a legal fight with Du Pont regarding a possible infringement of a patent belonging to Du Pont by AKZO on a similar aramid fibre with the trade name 'Kevlar'. AKZO was happy with Roebroeks' process, as it strengthened their legal position as well as increasing the

Geert Roebroeks, always looking for a practical solution.

number of possible application of the aramid fibre. A patent was filed, the first of many for Roebroeks. All the others would be on a new variant of fibre-metal laminates: Glare.

Glass versus aramid

We saw in the previous chapter that fibre failure occurred in Arall under a fatigue loading which simulates the pressurisation of a fuselage. This was attributed to insufficient bonding between the aramid fibre and the adhesive in the material, but the fibre also behaves poorly under compression loads. When the aramid fibre is crushed, as is the case when a fatigue crack in the aluminium layers closes and the fibre is compressed, it slips out of the adhesive and fails when it comes under tension again. According to Roebroeks' explanation of this fibre failure mechanism, roughening of the aramid fibres would not be adequate in this case. Another fibre had to be found that offered a better adhesion with the epoxy. Roebroeks studied models of the fibre failure mechanism in the lab for different types of specimens and extensively used the electron microscope to find clues to explain exactly how the fibre failed during fuselage loading. With an explanation a solution might be found. Several graduate students worked on this explanatory model, including Paul Matthey, who discovered fibre failure, Frido Smulders and Jan in 't Velt. They studied the imprints which were left after the fibres were pulled out of the adhesive and found marks in it that resembled the ones left in a fracture surface after a fatigue failure in aluminium. Under the microscope, single embedded fibres were pulled out of small adhesive samples in dedicated equipment to study the fibre pull-out process. Also, fatigue tests were performed on special specimens in which the fibre failure process could be monitored. One model survived all this experimental work. Roebroeks discussed the outcome with Vogelesang and his roommate Leo Meijers, who happened to have samples of a different fibre in storage in the cellar of the lab: the R-glass fibre from the French manufacturer Saint Gobain. A new fibre meant a new material. All the possible effects of a change from aramid to glass on the material properties were discussed by Vogelesang and Roebroeks. The experience with aramid Arall had created insight into the physical phenomena that played a role, and this helped them to predict the consequences of incorporating a new fibre into the laminate. Theoretically, carbon might also

do the job, but using carbon involved a risk: attaching carbon to aluminium can lead to galvanic corrosion, a corrosion type in which the less noble of two connected materials dissolves. A classical example of galvanic corrosion in engineering is the application of steel bolts in an aluminium structure. The combination of glass and aluminium does not pose this problem. Glass is an extraordinarily strong material, but it can be brittle if small cracks are present in it. However, in the form of a fibre, glass can be both flexible and strong. R-glass is an extremely strong variant of glass fibre. The first glass fibres suggested by De Bruijne and applied by Schliekelmann on the F-27 were of a weaker variant, the E-glass fibre. The R-glass fibre has a different composition and a better surface, and is therefore very strong. R-glass resembled the top secret American S2-glass fibre, made by Owens and Corning, which could not at the time be applied in fibre-metal laminates because it was considered to be a strategic material by the US government. Nowadays, S2-glass fibres can be used to make Glare.

Low-frequency fatigue machine made by Roebroeks for his PhD-research.

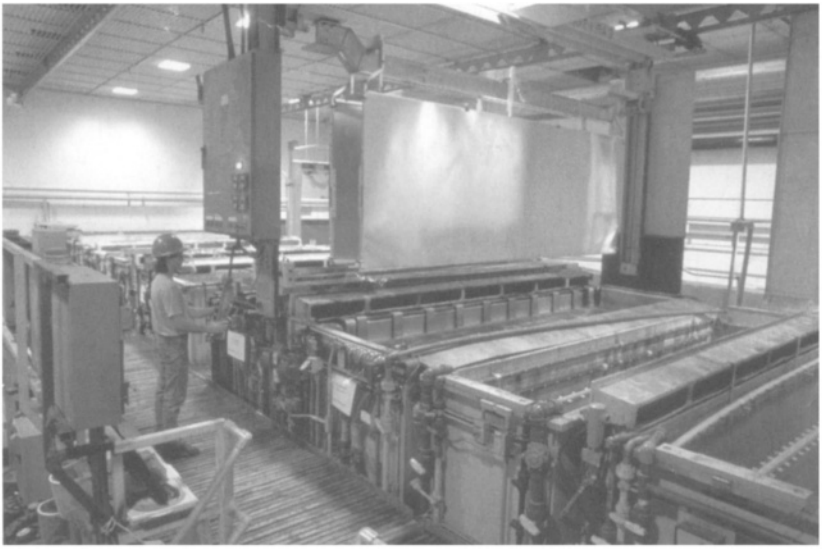
The day after the new concept was born in their office, Roebroeks and Meijers were winding the R-glass fibre with the lathe on aluminium layers and adhesive in the Delft lab to produce the first R-glass Arall laminates. The name Arall was so well-known that it was also used for the laminates with glass fibre for a while, even though it was actually an acronym of Aramid Reinforced ALuminium Laminates. A couple of months after the first successful trials with R-glass Arall, the first results were presented to the world at the first specialist conference in Seven Springs. After these findings, Roebroeks changed his PhD-thesis subject from fatigue of Arall in general to all relevant aspects of this new material. It was soon called Glare, derived from GLAss REinforced laminate. The name was carefully selected by AKZO's sales department, but not carefully enough as we will see in the next chapter. Roebroeks became the leading specialist on the material and found many other advantages of Glare: a high strength of the material with a hole (blunt notch strength) and with a crack through the thickness with the fibres cut (residual strength). For one of his test series, he made his own low-frequency fatigue machines in the same spirit as he maintained his Deux Chevaux. Roebroeks finished his PhD-thesis on Glare in 1991.

A patent was immediately filed by AKZO on the 14th of October 1987 covering the new Arall variant, with Roebroeks and Vogelesang named as inventors. At the end of 1989, the European Examiner rejected this patent on R-glass Arall because it was not innovative enough and it was considered to be too obvious. The scope of the patent claims was therefore reduced and the claim itself strengthened. There appeared to be a similar patent already in existence, and this meant that the new claim had to be made more specific: specific metal thickness and glass properties were mentioned, the difference relative to laminates with E-glass was shown, and the improvement relative to Arall was explained. This is the normal process. Usually the claims of the patent are described as generally as possible to cover the largest area possible, and only when this is not accepted are the claims made more specific. The patent in its final form was issued in Europe on the 27th of March 1991, and in the U.S. on the 4th of July 1991. During the same period, in April 1991, even the basic Arall patent was still under attack, this time by the Japanese company Sumitomo which considered it “not innovative”. This level of interest and opposition clearly showed the significance of the patents.

Arall production

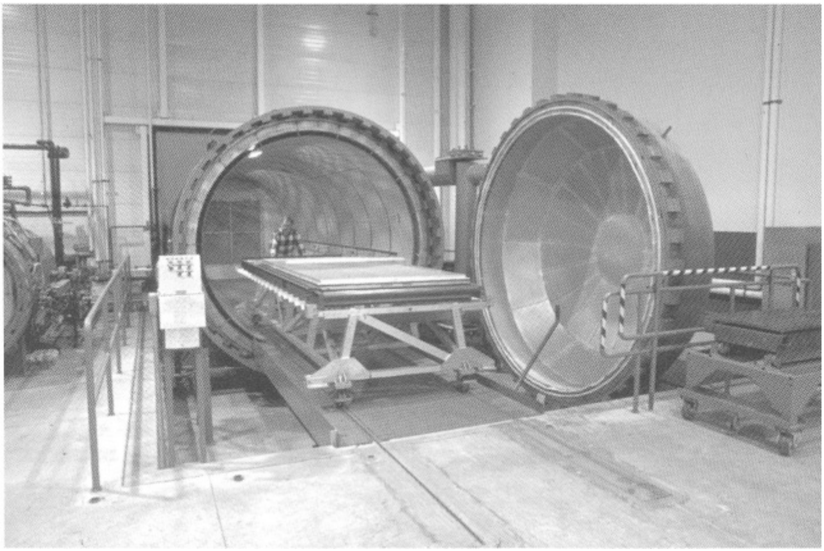
ALCOA was not happy with the news in 1987 of a new product just at the moment that the product life cycle of the first one was starting. Expensive qualification work needed to be carried out on the Arall-3 material to be able to apply the material on the C-17 aft cargo door. This expensive qualification is necessary for each new type of aircraft material to guarantee production quality and to specify minimum material parameters like strength, which can be used by aircraft designers. Hundreds of specimens from different production runs have to be tested for tensile strength, compression strength, shear strength, and so on for statistical reasons. For Arall, this also meant different production runs for the ingredients: metal layers, metal pretreatment, fibres and adhesive, as well as the final autoclave cycle to bond the laminate and even the stretching process after the cure. The high costs required for qualification form a big obstacle for new aircraft materials, since qualification is only started when it is clear that the material will be applied, and aircraft designers are not inclined to design their structures from materials which are not yet qualified. This is a clear example of a chicken-and-egg situation. Qualification for metals is easier to obtain than for composite materials, whose strength strongly depends on the specific fibre orientations in the stacking sequence (lay-up) of the different fibre/plastic layers of the material. Arall-3 could be qualified for the C-17 according to the metal procedures, proving the advantage of this hybrid material. The 'Metal Volume Fraction Approach' was found to be a very strong approach for the qualification of Arall. This meant that one Arall-3 thickness could be qualified and that the strength properties of other thicknesses could be calculated from the relative fraction of the metal relative to the total thickness of the Arall laminate. A linear relationship was proven between the strength values and this metal volume fraction. However, even with this simplified qualification process, hundreds of specimens had to be tested for this single Arall type.

After qualification, the Arall-3 material could be applied in the C-17 cargo aircraft of the US Air Force. The tail section of this aircraft was too heavy and therefore a desperate search for possible weight savings in the back made the application of Arall possible. The aft cargo door of the C-17 consists of two parts: a lower section which hinges down and is used as a ramp for loading the cargo bay of the aircraft and a second part which lifts up to enlarge the size of the opening of the fuselage. The latter part had a size

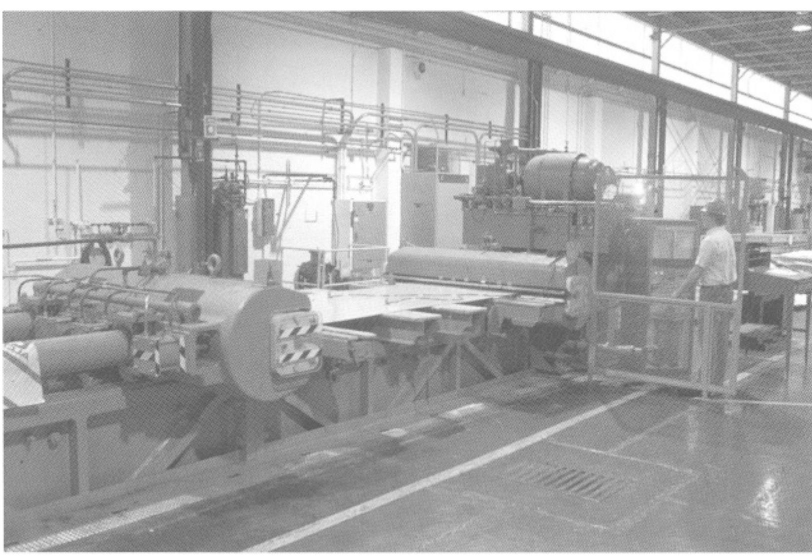


Aluminium sheets are given a pretreatment bath at ALCOA for Arall production.

Primer application on aluminium sheets at ALCOA for Arall production.



Autoclave at ALCOA used for Arall production.



Stretching of an Arall panel after curing at ALCOA.

of 5.6 x 9.7 metres and the outer skin of it was made from Arall. It is a fuselage structure but, unlike other parts of the fuselage, it is loaded in one direction only, i.e. in the length direction of the aircraft, since the door is free to move in the other direction and is not mounted to the rest of the fuselage structure. This unidirectional loading resembles the situation in a wing panel, the structure that was studied so extensively in Delft for the Arall development programme. Because of the unidirectional loading Arall, which had fibres in one direction only, could be applied here.

However, the Arall cargo door appeared to require an extremely elaborate production process. The structure is curved in two directions and therefore the Arall panels were stretch formed into the right contours. Because of the enormous size of the door and the limited size of Arall sheets, the door had to be constructed from around twenty parts which had to be connected by titanium straps and by fasteners. The titanium parts also had to be manufactured to fit the contour and the drilling of the rivet holes through a package of Arall and titanium proved to be a delicate process. The limited size of the Arall was caused by the thin aluminium sheets in the laminate. These sheets of 0.3 to 0.4 millimetres were hot rolled to this thickness in the ALCOA plant in Davenport near Pittsburgh, and due to the high forces that had to be exerted on the material to reach this thickness, there was a limit to the length of the rolls and therefore to the width of the aluminium sheets. The rolls would bend too much when the width was too large and this would, in turn, create a varying thickness over the width. Moreover, when the aluminium ingots are rolled down to the thin sheets cracks are created at the edges of the sheets which may even lead to rupture of the sheet and stop the rolling process. When this happens, the product is not accurate enough and has to be scrapped. The importance of the limitation on the size of Arall sheets will return later in our story, since it had to be solved to apply the material in the gigantic structure of the A380 super-jumbo.

In August 1990, Fokker got a license to produce the laminate free of charge because it was also seriously considering applying it in the Fokker 100. A glorious future seemed to be at hand for the material, but at the same time cracks appeared in the relationship between the American aluminium producer ALCOA and the Dutch aramid producer AKZO. The Wall Street Journal reported on the chilly relationship between the two just after Arall was used for the first time in a real aircraft, the C-17. Rivals seemed worried: "'When it was part of the big ALCOA, I didn't consider it competition," says

Marc Verbruggen, marketing director for AKZO's rival product, Glare. "Now, he says he does." AKZO's Glare even became a competitor of ALCOA'S Arall for a while.

AKZO versus ALCOA

It was remarkable that ALCOA had the license to produce Arall with aramid fibres, which were produced by AKZO, whereas AKZO owned the patent on Glare, which did not contain ingredients produced by AKZO but did contain thin aluminium sheets of widths that could only be produced at the time by ALCOA. AKZO held the patent on Arall and later on Glare, and had played the game in a very clever way. The company had granted ALCOA the exclusive rights to produce and commercialise the material for five years. This period would eventually expire and from that moment ALCOA would have the non-exclusive rights to produce the material. In this way AKZO could gauge the market response. The five-year period expired in 1988 and clearly there was a lot of interest in Arall, as revealed by the first specialist conference in Seven Springs. ALCOA hoped to start to routinely fill orders for Arall from 1988 onwards.

In view of this, AKZO was now aiming at a fifty-fifty partnership and joint venture with ALCOA on the laminate. Since ALCOA had a very strong position in the aerospace market, the company was not inclined to grant AKZO a position in a joint venture because this would allow AKZO to penetrate a market that was not theirs. Instead, ALCOA trusted its own research and development at the ALCOA Technical Center. The cracks in the co-operation between the two companies emerged just at the time of the second Arall specialist conference in Delft. Both companies still co-hosted the conference dinner at the end of the conference and presented a gift to all participants: a small digital alarm clock in a plastic casing that could be opened by sliding the two halves of the casing apart, after which the clock would pop out. Ironically, the two plastic halves had the company logos of AKZO and ALCOA printed on them and the present therefore also symbolised the impending separation of the two companies. The day after the very successful technical conference, the relationship broke down completely.

ALCOA felt that Delft sided with AKZO in the conflict. Bill Evancho had just taken over from Larry Mueller, who had headed the Arall laminates

group in the early days. Evancho was a metallurgist by education and through his early career at ALCOA who had moved into management. After participating in the team responsible for restructuring ALCOA'S aluminium company and then moving on to become President of Alcoa Steamship Company, which he also restructured, he had a solid reputation. He also had solid beliefs: for a long period he had anticipated that aluminium, which once was a high tech aerospace product, would eventually become a commodity product and be replaced by engineered materials. When he read an article on Arall in ALCOA's company magazine, *The Alcoa News,* he sought the leadership position of the Arall laminates project. He still maintains his belief in fibre-metal laminates today.

Evancho's first task was to solve the license issue. ALCOA was involved in Arall from the very beginning and the relationship was clearly more than a commercial one. After Evancho's first visit to Delft, in March 1989, Vogelesang wrote: "It was for us very painful to hear from you that some people at ALCOA are feeling themselves betrayed by us. To the bottom of my heart I tell you that they have no reason at all to think like that... But one thing is essential for us, there needs to be a full understanding and confidence between both our groups." This reflected the personal relationships, and even friendships, built by Vogelesang during the whole development of Arall and Glare with different industrial partners. In August 1989, a proposal was made for an agreement between ALCOA, AKZO and Delft. ALCOA wanted to share the rights on Arall and Glare in Europe with AKZO, whereas AKZO would not be a partner in the U.S. This was not acceptable for AKZO and hence a stalemate developed. ALCOA therefore paid another visit to Delft to attend a meeting in October 1989. The meeting laid out three possible options for the co-operation between ALCOA and AKZO: a joint venture, 'friendly' competition, or 'cut-throat' competition.

If the last option became a reality, the connection between ALCOA and Delft, which was almost as old as Arall itself, would be cut. Delft asked ALCOA to agree to the first option, effectively negotiating on AKZO's behalf. Boud Vogelesang wrote to Bill Evancho just after the meeting: "I am hopeful that we can find a solution for the sad situation in which we are landed." Bill Evancho proposed that both AKZO and ALCOA would provide financial support for Delft and that the efforts on Arall and on Glare be separated. Vogelesang did not like the idea and wrote back: "Due to the problems between AKZO and your company, Delft University has been forced into an awful position between the two companies." Indeed, Delft was torn apart

between friendship with ALCOA and with AKZO, but it was clear that the ties with the Dutch company would prove to be stronger.

At that point AKZO was in a phase in which it wanted to create new products outside its core business as a producer of bulk chemical products and therefore the company did not yield to ALCOA. It founded a department ‘New Business’ headed by Eiso Albeda van Ekestein who hired Verbruggen and later Roebroeks, Gunnink and Van Oost to create a Glare business. AKZO had sponsored Roebroeks during his PhD-study and he had already joined the company by the time he defended his dissertation. Gunnink took the big step from the university to the corporate world in 1990 when he was recruited by Albeda van Ekenstein and Verbruggen after commenting that AKZO’s competitor ALCOA was a material producer lacking a designer. Without design knowledge, ALCOA did not know what their customers really needed. This was a recent trend in materials development. In the past, materials production and structural design had been separate areas. The designer thought that he only needed the strength data of the aluminium alloys to be able to design a safe structure. For composites, and also for Arall and Glare, the difference between the material as a clearly defined semi-finished product (for example sheet material) and a structure was much smaller. Indeed in composites, tailored production of the material, with fibres in the right location and laid in the right directions, produced a structure instead of a material. In this way, material and product were becoming one and the same thing. The material’s supplier, therefore, provided more and more design support. Gunnink’s move as an aircraft designer to AKZO was therefore not a coincidence but it reflected a trend in material production. Rob van Oost was the second designer at AKZO and joined the company after his graduation from Delft, where he had worked on a C-17 wing study in Gunnink’s structures group, at the time that the C-17 was creating a lot of development and design work for possible applications of Arall.

AKZO was aiming at a joint venture for Arall and Glare with ALCOA, and with the brand new Glare patent it possessed an important playing card in this management game. On the other hand, AKZO was an insignificant player in the area of aircraft materials, a severe handicap for such a dedicated niche business. The stakes were high and AKZO was even prepared to go out on a limb by creating its own production facility together with Fokker. To steer the production process, Roebroeks agreed to leave his dike house and move to Amsterdam.

At the same time, however, Fokker was also building a large new facility for the manufacturing of composite and bonded structures at Ypenburg near The Hague. It was agreed that AKZO would open a Glare manufacturing unit at this location. In this case, R-glass Arall would be produced by a joint venture of Fokker and AKZO. The aluminium was supplied by the aluminium producer Kaiser and also a new fibre/adhesive prepreg was selected, with Cytec adhesive from Ciba Geigy replacing 3M's AF-163. The world of aircraft composites was changing rapidly, which heightened the importance of trade names. The battle focused on the names 'Arall', registered to ALCOA, and 'Glare', owned by AKZO. In the aircraft manufacturing world nobody knew AKZO, and in this sense ALCOA had nothing to lose against the small group in that tiny country. Glare was hardly known outside Delft and ALCOA gladly kept it this way, commercially promoting Arall. Apart from the use of Arall in the C-17, the US Air Force was also very busy with the study of other promising applications, like the flaps of the C-130 Hercules and the dorsal covers of the T-38 jet trainer. Captain Rob Fredell and the Aeronautical Systems Division's Laboratory at Wright Patterson Air Force Base in Ohio were very active in this area.

Bob Bucci (right) and Michael Gregory (left) of ALCOA review a collection of potential Arall applications.

De Havilland Canada also investigated this bonded laminate and found the material held up remarkably well against lightning hits. In thunderstorms, an aircraft may be hit by lightning. While aluminium alloys melt under a lightning strike and many composite structures even have the tendency to explode since they cannot transmit the electrical discharge fast enough, Arall appeared to have superior qualities. Only the outer aluminium layer melted and the aramid shielded and protected the other aluminium layers. The inner layers remained intact and the damage was minor. By the same token, Arall appeared to be well suited for use in fuel tanks. Here skin thickness was sometimes increased to provide extra heat resistance. This was yet another favourable property for the material that had primarily been designed to have good fatigue characteristics. Arall's future looked bright and ALCOA'S marketing position was very strong. The fact that ALCOA backed the material reassured the aircraft manufacturers, who had been in business with the aluminium producer for decades.

Joint venture

However, Vogelesang, Gunnink and Verbruggen attacked the position of ALCOA by making a three week tour around the world to visit all the important aircraft manufacturers – in Canada, in the U.S., in Indonesia, in Japan, and in Europe. Since AKZO had no contacts, all relevant contact persons had to be traced without the help of the marketing experts that ALCOA had at its disposal. Everywhere they went, Vogelesang, Gunnink and Verbruggen showed the same overhead slides with evidence of the excellent properties of Glare against the disadvantages of Arall. Since Arall had been invented in Delft and Vogelesang had originally backed it strongly, their story made a good case.

The success of the tour made the ALCOA management realise that the market for Arall had vanished into thin air. ALCOA was actually brought to its knees. AKZO also realised that they could not make it on their own and finally, in the autumn of 1990, an agreement was reached. The partnership between AKZO and ALCOA was formalised in 1991. An agreement to found the Structural Laminates Company (SLC), a joint venture of AKZO (1/3 owner) and ALCOA (2/3 owner), was signed on the 1st of June 1991.

The group was back together again, which was a relief for Delft because it had felt squeezed between the industrial partners. The agreement

provided for production to be concentrated in New Kensington, Pennsylvania, while the research, development and marketing would be done in Delft. For this reason a separate company, a subsidiary of SLC with the name Structural Laminates-bv was founded in the Netherlands, headed by Gunnink. Structural Laminates-bv was located in Delft in the same building as the Faculty of Aerospace Engineering and its employees Gunnink, Roebroeks, Van Oost, Leonard and later Buwe van Wimersma, Greijdanus and Mattousch, were actually integrated in the Structures and Materials Laboratory, forming one team with the university staff: Schijve, Vogelesang and myself. Thus a strong Delft team was created, whose success would attract numerous students in the years to come.

The application of glass in fibre-metal laminates and the backing of ALCOA opened the door of the world’s largest aircraft manufacturer: Boeing. Boeing did not like the aramid fibre because of its bad experience with moisture absorption and consequent degradation of the material properties. Rob van Oost was sent by SLC to Seattle in 1993 to do design studies in co-operation with Boeing designers in the New Large Airplane group, which was studying a successor to the Boeing 747 Jumbo Jet. It gave the people from Delft the opportunity to have a look ‘in the kitchen’ of this important aircraft manufacturer, and indeed Boeing treated aircraft design according to the recipe in a cookbook. The company had a handbook approach for the design of aircraft according to fixed data and design tools, which accommodated the hire-and-fire policy of designers for different projects. The Boeing approach did not exactly mesh with the more flexible culture of Delft. Van Oost did not have enough data to study the application of Glare in this large aircraft and instead he studied the application of Glare in the Boeing 777, a new Boeing aircraft that was then in its final stage of development. Boeing and ALCOA had a very close relationship and Glare was just in time for Boeings’ new aircraft.

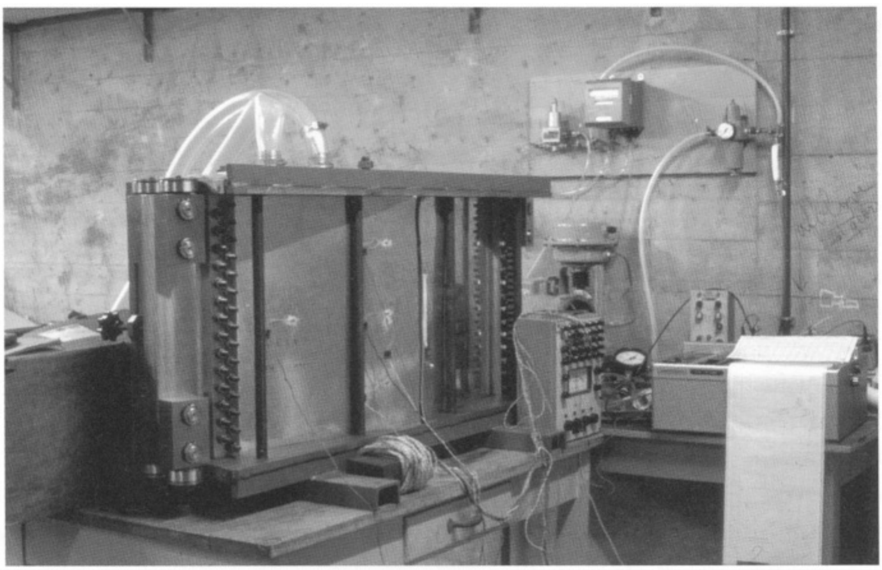
Impact and other properties

It was, however, too late to consider Glare for the vital parts of the aircraft, though the material properties of Glare could be useful for other parts. Whereas Arall had bad resistance to damage from objects which hit the structure, the so-called ‘impact resistance’ research that I had done in Delft had shown that at low velocities Glare is as good as aluminium and

superior to carbon fibre composites, while at higher speeds the glass fibre in the laminate becomes much stronger and the impact properties much better than those of aluminium. In 1991 I finished my PhD-thesis on this research. A drop-weight tester was built in the lab to drop a projectile in a controlled way on sheet specimens and the contact force between this object and the tested sheet measured during the milliseconds of contact between them. Later, a gas gun was designed and built to propel projectiles at velocities of several hundreds metres per second. During the small time period in which the projectile and plate come into contact, the velocity of the projectile is reduced as the energy is transferred to the sheet, inflicting damage. The tangible result of this study were boxes with hundreds of dented and cracked Arall, Glare, composite and aluminium specimens, while my ears were ringing from all the 'bangs' that were created. Roebroeks, Chen and I had formed a team of PhD-students under the critical supervision of Schijve – a team that was initiated, guided and propelled by Vogelesang. My work showed that Glare is not only more resistant to impact than other materials, but also that the damage – permanent deformation and the denting of the aluminium layers in the laminate – can be found easily with the naked eye. This permanent deformation of a material after loading is called 'plasticity'. Composites do not deform plastically. Hardly any dent is created and therefore damage is much more difficult to detect in this type of material. Also, the mechanical properties of Glare after impact damage was created appeared to be better. In 1990 the excellent impact properties of Glare were put to work in a cargo floor in the Boeing 777, an application that was mainly due to one person: Boeing engineer Ted Reinhart. Glare was selected because floor structures are particularly prone to impact damage. This was the first commercial application of a Glare product, although not in a primary structure (for which Glare had been designed) but a secondary one. The primary structure is the part of the aircraft that is carrying the flight loads and is essential for the safety of the plane, whereas secondary structures in an aircraft can fail without directly jeopardising safety. It is therefore easier to apply a new material to secondary structures. A special variant, Glare-5, was later developed especially optimised for impact properties, and consisted of more glass fibre layers than the regular Glare types.

Apart from its excellent impact properties it was also found that Glare had good burn-through resistance. Boeing did fire resistance tests up to temperatures of 1200 degrees Celsius and showed that Glare could prevent fire from penetrating for more than fifteen minutes. Although the outer

aluminium layer would melt, the glass fibre proved to withstand the flame temperature. When the adhesive carbonised the layers separated, effectively creating an insulating effect, and the inside temperature was of the order of only 100 degrees Celsius. Both the impact and fire resistance properties were applied in a blast-resistant container that was tested by the FAA in 1995 as an answer to the Lockerbie crash over Scotland. This container was given the name ECOS-3 and was developed by Galaxy Scientific Corporation. It is now in production.



Test setup designed and used by Chen to load a curved fuselage skin by internal pressure.

Toward fuselages

Up to the end of the eighties, the design studies on Arall had concentrated on wing applications, a very primary structure indeed. Design studies that started in these days on the C-17 horizontal stabiliser revealed that for such large and therefore thick structures Arall would become a very expensive material with too many layers which were difficult to produce and inspect. Although cracks grow very slowly in Arall, inspection to find cracks would still be needed. However, finding such cracks would be difficult in the

hidden aluminium layers inside the laminate. Special techniques can detect interruptions of created magnetic fields in the laminate, caused by cracks, but this so-called 'eddy current inspection' becomes more difficult when the laminate is thicker. Gunnink came up with a new idea, a typical designer's solution. In 1990 a patent was granted on tapered Arall and Glare with Gunnink as inventor. For this concept a common tapered wing panel, produced by machining out of a thick aluminium sheet, was taken and strengthened by an Arall or Glare top layer. The idea was to combine the conventional way in which producers make wings by machining and the Arall concept. Since only Fokker was used to assembling a wing by bonding, a complete Arall or Glare wing structure would be a bridge too far for most producers and this concept created a bridge.

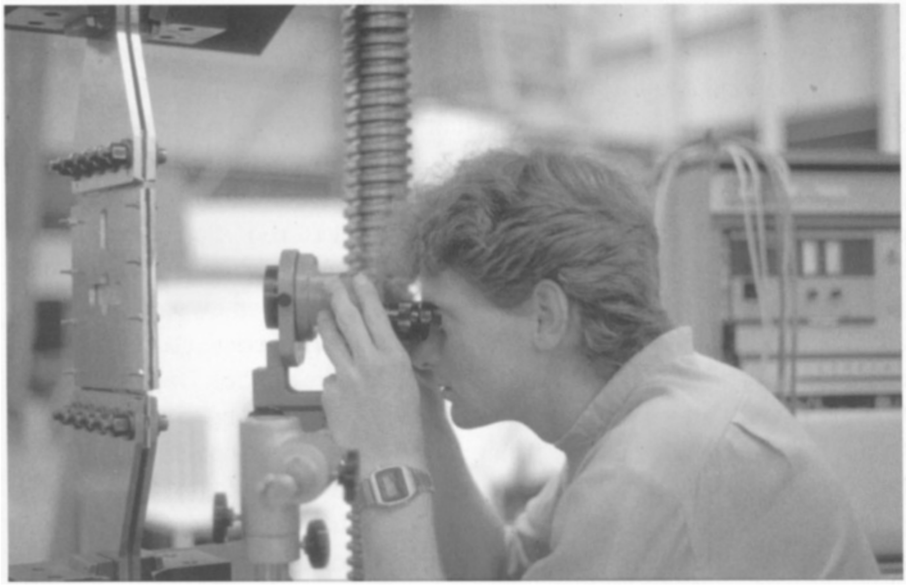
Gunnink's idea was clearly a desperate move and a kind of add-on to a conventional structure to force the laminate into it. Moreover, composites were advancing in aircraft engineering and after application in flaps and tailplanes all efforts were now concentrating on the use of carbon composites in the wing. This seemed the logical next step for composites. The industrial forces that were pushing composite materials onto planes, were much bigger than those that could be exerted for Arall and Glare at that moment. The first decade of Arall and Glare was spent on wing studies while the future for the material now appeared to depend on the fuselage skin. It was under fuselage fatigue loading that the fibre failure mechanism for Arall was discovered, for which Glare appeared to be the answer, and Delft was soon devoting a lot of attention to fuselage applications. The PhD-subject of Dong Chen was on fuselage loading conditions for Arall and Glare. The fuselage skin was still the unchallenged territory of the metal specialists and the Glare material fitted their specific mindset. The last development in fuselage skin materials had been the change, in Anthony Fokker's days, from a structure of welded metal tubes covered with fabric to the aluminium alloy 2024 used for the DC-2 fuselage. The same alloy is still in use in aircraft built in the 1980s and early 1990s. The fuselage specialists were longing for new developments and personal challenges while their wing colleagues could do magnificent work on composite wings.

However, in this area where aluminium was unrivalled, ALCOA made its biggest profits and soon SLC started to compete with its mother company. In the autumn of 1991, the top manager in ALCOA responsible for Arall and Glare was replaced by someone opposed to fibre-metal laminates. The new

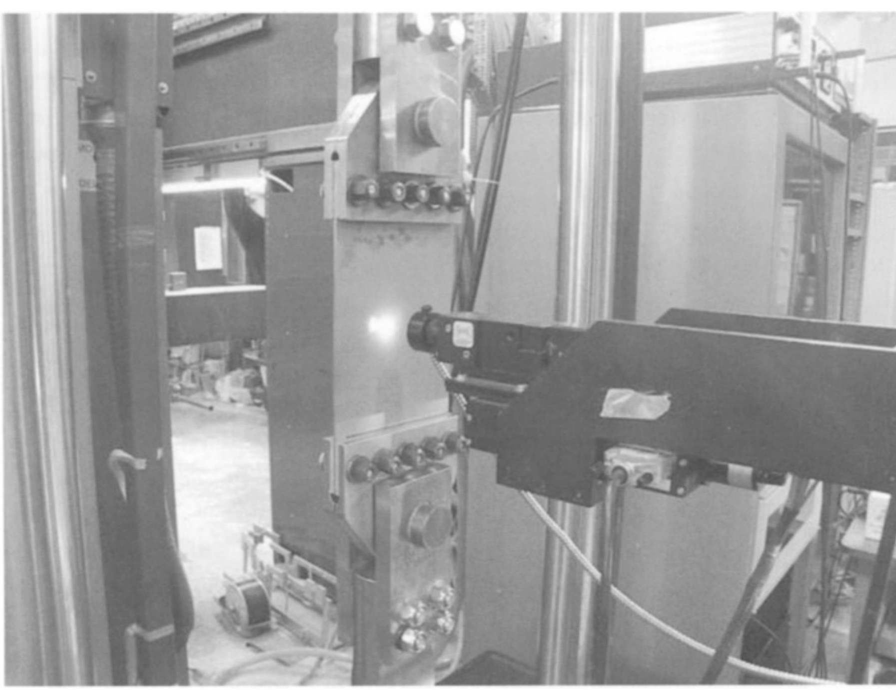
man saw the laminate primarily as a material suited for floors, and this created a negative environment for the wider application of Arall and Glare.

To complicate things further, ALCOA had developed new aluminium alloys, such as an alloy of aluminium with lithium, as an answer to composites. Far more money than had gone into the development of Arall and Glare had already been spent on this alloy, so far without producing a good product. For ALCOA it was decision time; it could not afford to keep all its options open. Having invested in composite materials, aluminium alloys and fibre-metal laminates, ALCOA now decided to concentrate on its core business, aluminium. For the Boeing 777, ALCOA developed a special alloy designated as ‘C188’ and later given the systematic code 2524, signifying that the alloy is a derivative of the familiar 2024 alloy already applied in the DC-2. Boeing and ALCOA even had an agreement giving Boeing the first right to apply the alloy, a fact that made Airbus Industrie, the European competitor of Boeing, furious. It was the first time that the use of a new aluminium alloy was restricted. The C188/2524 alloy had excellent damage tolerance capabilities, which meant that an aircraft fuselage constructed from this material could withstand a large crack, caused by fatigue or the impact of engine fragments. Therefore the fuselage of the Boeing 777 did not need the titanium crack stoppers which were still needed in the Airbus aircraft to give the fuselage the capacity to carry internal pressure with large cracks. Titanium is an expensive material and the cost of manufacturing products from it, and drilling holes in the combination of titanium and aluminium, made the titanium crack stoppers very costly.

Whereas the deformation of a wing resembles the bending of a beam, the fuselage of an aircraft can be seen as a big balloon that is inflated every flight during the climb to provide air for the passengers and deflated during descent. The skin of this balloon is of the order of one to two millimetres thick and is supported by stringers along its length and frames around its circumference. Like a balloon, a fuselage will explode when a crack with a certain length is present in the skin. To be damage tolerant, the fuselage has to be able to withstand a given crack size, usually with a length of two frame bays. Inflating the fuselage leads to loads in two directions in the skin, with the loads in the circumferential direction twice as large as the loads in the length direction of the fuselage. Therefore, the fuselage will usually burst length-wise when things go wrong. A wing is a large cantilever in bending, which creates loads mainly in one direction: tension in the lower part of the wing and compression in the top part of the wing when the wing



Student monitoring a crack in a test specimen.



Digital camera monitoring a crack in a test specimen.

bends upwards during normal flight. Because Arall was designed for wings, fibres in one direction were sufficient. Adding fibres in the other direction reduced the load carrying capacity of the material relative to its thickness in such a way that it was lower than that of aluminium. The poor adhesion between the aramid fibre and the adhesive meant that it was also not possible to add more fibres in the other direction without adding more adhesive to the material, because delamination would easily take place with too many fibres. Adding more adhesive would require too much weight. Also, Arall had to have permanent strain induced in the fibres by stretching after autoclaving. This required large sheet stretchers and because of the length of the Arall panels, they could not be stretched in the transverse direction. For the glass fibres in Glare, the fibre content could be higher and the fibre/adhesive layers could be thinner. The glass volume content relative to the adhesive was around 60 percent, while for aramid the limit was 50 percent. In 1989 the thickness of the glass fibre/adhesive layer was reduced from 0.16 to 0.125 mm for fuselage applications. Glare appeared to be ideally suited for fuselage applications. Apart from Glare-1 and Glare-2 which were unidirectional and resembled Arall-1 and Arall-2 respectively in 1990 'cross-plied' variants were defined for fuselage applications: Glare-3 with 50% of the fibres in one direction and 50% in the direction perpendicular to it and Glare-4 with twice as many fibres in one direction as in the other direction. Glare-4 was especially suited for locations in the fuselage where the load in one direction was twice as high as in the other direction, whereas Glare-3 was designed for the uppermost part of the fuselage where this ratio is one-to-one, due to the combination of pressure loads and the bending of the fuselage under its own weight.

Retreat of ALCOA

In the early 1990s, composites were no longer considered a serious threat to ALCOA'S market share. The introduction of composites took much more time than had originally been anticipated and the first maintenance experience of composites in commercial aviation was disappointing. More than 80% of a commercial aircraft was still made of aluminium. Glare was now in direct competition with non-laminated aluminium products and was a potential threat to ALCOA'S core business because it could replace aluminium alloys in aircraft fuselages. On the other hand, the production of

thin sheets for Glare also posed economic threats. Producing the metal for the laminate was a laborious process, which ate away at the production of ALCOA'S premium products. The production of thin sheets was done in the mills of Davenport, at the same location where the aluminium alloys like 2024 and 2524 were produced. It also proved difficult to produce the thin gauges required for Glare. The recovery – i.e. the success rate of sheet products with the right quality – was therefore very poor. A lot of scrap was created and much precious production capacity was required to produce the thin sheets for Glare. It did not take a lot of arithmetic before the new management of ALCOA figured out that it was loosing a lot of money on Glare. ALCOA management even encouraged SLC to buy the thin sheets it required from its competitor Kaiser. The partnership of ALCOA and AKZO started to show cracks, but this time the process went very slowly. The problem for ALCOA was that its customers liked Glare as a product. Boeing was still doing design studies and Airbus became especially interested, as will be seen in the next chapters. However, without ALCOA'S strong support for Glare, Boeing's interest diminished. The feeling became strong that Glare would be too expensive. The rift between ALCOA and AKZO lasted until 1995.

By the mid-1990s, the application of Glare for fuselage floors, which originally occurred in the Boeing 777, had become a hot topic. Floors are usually not a primary structure, but they are sensitive to impact damage and the regulations of the airworthiness authorities demand that damaged cargo floors should be repaired to restore the fire resistance of the cargo bay. This means the maintenance cost and the down time related to cargo floors can be substantial. United Airlines did a survey of different systems on the market and specified Glare as a replacement material in the bulk cargo bay floors of its Boeing 757 fleet. However, the contract was not given to SLC, but to a well-established producer of aircraft floors. This created a patent infringement. AKZO insisted that pressure should be put on the manufacturer and legal action be taken as a countermeasure, to which ALCOA only responded reluctantly. The serious interest which was growing at Airbus, who were considering applying Glare in fuselages, flashed warning signs at ALCOA since it had invested a lot of money to develop alloys like 2524. Once again, the company wanted to break up the joint venture. ALCOA convinced AKZO to shut down the manufacturing facility of SLC because of the slow acceptance of the laminates in the market place

and ALCOA informed their customers that it was questionable whether they could continue to purchase Arall and Glare in the future.

This meant that Boeing started to look for another supplier for the cargo floors and also started to buy material from the company that had infringed on the patent and now was producing a similar product. To make things worse, due to ALCOA's attitude, McDonnell Douglas started to study an aluminium replacement for the C-17 cargo door and found that significant cost savings could be made. Only approximately forty C-17 aircraft would eventually be equipped with Arall doors, while the newer aircraft received aluminium doors. ALCOA stopped the production of thin aluminium sheets for the laminates around 1997 and concentrated on making its profits with 2524.

The study collection is removed from the lab floor before a soccer game.

By then, ALCOA's potentially most important American customer had turned its back on Glare. In 1993, only three years after first applying Glare in the Boeing 777 cargo floor, the Boeing management decided to put a moratorium on Glare studies in Boeing. ALCOA did not support the material anymore and the price was considered a problem. Boeing complained that the price of Glare was prohibitive because the sheets of Glare were too narrow for many applications and that too many costly joints would be

needed to apply Glare as a structural material in an aircraft fuselage. Nonetheless, hopes remained high in Delft for the long-term prospects of Glare. Just after the break with Boeing a technology meeting of SLC and Structural Laminates-bv was held in Delft to discuss future prospects in the light of this new situation. During their flight home from Delft, a member of the SLC crew quipped: “We can make wider sheets by placing the thin aluminium sheets side by side and covering them by fibre/adhesive. Because the available autoclaves are big enough this package could be cured and nobody at Boeing would see the gaps between the aluminium layers!” The discussion that took place in the plane after this remark indicated the possibilities of this idea. SLC quality manager Carl Garesché was the main inventor of the concept. Delft took the idea and developed it into a viable solution. Although a lot of work still had to be done to prove the viability of this concept, a patent was filed for ‘spliced Glare’ soon after the flight, with Garesché and Delft engineers as inventors. The main problem was that the strength reduction caused by the interruptions of the aluminium sheets had to be restored. Initially this was achieved by adding material in the form of doublers on the outside of the laminate as a kind of bridge. However, this was not adequate. It was found that the sheets could be internally bridged by adding aluminium strips on the inside to restore the local strength, so-called ‘internal doublers’. This appeared difficult to produce, and while standing with a cup of coffee watching a fatigue test running on a spliced laminate, Geert Roebroeks and I came to the conclusion that the best option would not be to create gaps between the aluminium sheets but to overlap them by adding some adhesive film in between. Spliced Glare would make wider sheet sizes possible. It also introduced the possibility of producing double curved sheets without the need for expensive stretch forming. The splice concept paved the way to major cost reductions and large-scale applications of Glare. However, for Boeing it was too late. From 1993 onward, Glare could only penetrate the market for primary aircraft structures in Europe.

In 1997 differences between ALCOA and AKZO escalated, resulting in an agreement for SLC to stop all commercial activity and license the technology out. ALCOA wanted to keep control over Glare in the U.S. and therefore SLC was kept alive as a ‘paper’ company in control of the patent rights in the U.S., and as a joint venture with AKZO. SLC gave a license for secondary applications, including floors and cargo containers, to the company Aviation Equipment, Inc. Maintaining his belief in engineered

materials, Bill Evancho retired from ALCOA and joined Aviation Equipment, Inc. AKZO acquired the license in Europe in order to co-operate with Airbus and assumed responsibility for Structural Laminates-bv, restructuring it as Structural Laminates Industries (SLI) for this purpose. ALCOA thought that this was harmless because of the limited credibility of AKZO in the aerospace industry. Little did they know what would happen next.

4

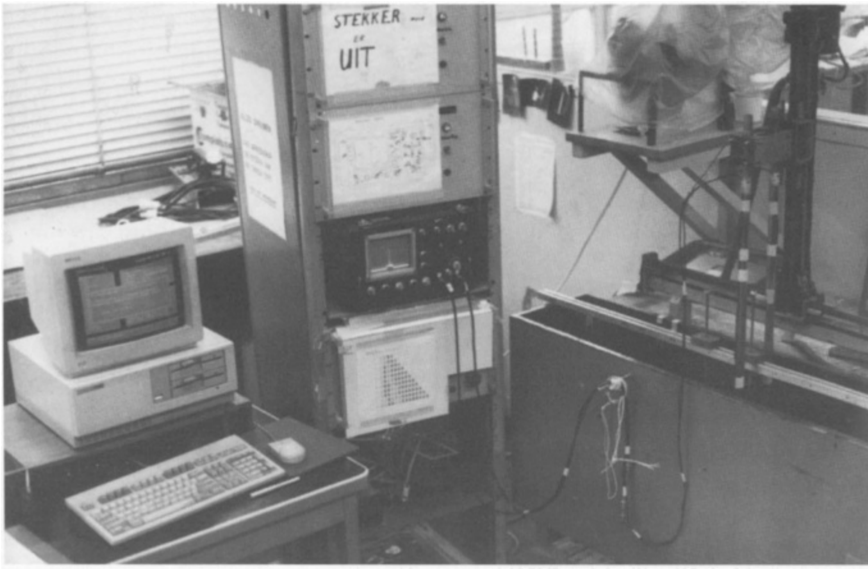
Glare in Europe - a long, long runway (1988-1997)

Educating students

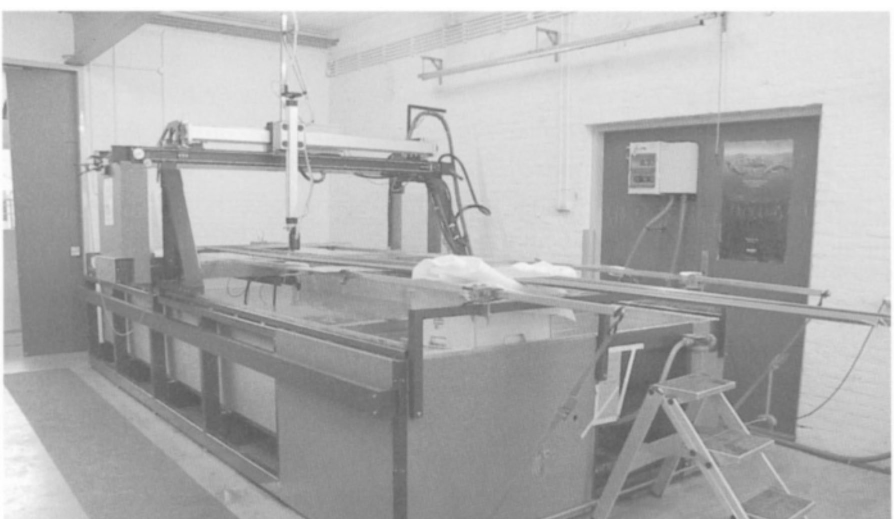
Schijve concentrated his scientific career on the subject that had also made up the topic of his dissertation, i.e. fatigue, and became one of the world's leading specialists in this field. At the same time, Vogelesang and Gunnink fought for the success of Glare. They kept SLC, and later SLI, alive and built personal networks in the aerospace and metallurgical industries. Although Schijve and Vogelesang had a global orientation, they did not neglect the Faculty of Aerospace Engineering, nor Delft University as a whole. In their roles as teachers, they stimulated students to carry out research. In the spring of 1992 Schijve started his last cycle of lectures before his retirement, as motivated as he had been at the beginning of his career. He and Vogelesang both took part in the fierce debate, then ongoing in the Netherlands, on the future of education and research at the universities in a time of recession and budget cuts. The university entered a new period in which income from contract research was of increasing

importance. The run for money had started. For the pragmatic structures and materials group this was not a big problem, as their speciality could be widely applied. However, for other groups in the faculty, like aerodynamics, it was not so easy to acquire money from industry. The university entered a dynamic period in which current events stimulated different, moving targets: a faster flow of students through the curriculum as a result of improvements in the education system, higher efficiency, a merger of faculties, increased top-down control by university management, interdisciplinary research, a higher output in terms of publications, a higher output in terms of citations, a higher position in international rankings, internationalisation, and – finally – a swing back to more fundamental instead of applied scientific research. A never-ending stream of reorganisations swamped the university campus. The time when a university career meant less stress and more opportunities to concentrate on personal interests than in commercial business had ended. University staff members had to qualify as ‘sheep with five legs’. Requirements were such that one had to be able to acquire money for academic research, deal with industry for contract research, be a stimulating teacher, innovate by incorporating new educational methods and resources (such as using computers and the Internet), manage faculty affairs, and – last but not least – be a recognised specialist in one’s field with an international reputation, flying to conferences and meetings all around the globe. Professors were constantly monitored and ranked by government organisations, university management and the media, and were no longer sovereign kings in their research groups. In some ways it helped to tear down the ivory towers, blow away old dust and stir up the university. In other ways the pressure was too much and the many changes left no time for reflection. The constant scrambling after the latest fashions drew attention to management tools and away from the contents of the work and long-term strategies. The academic year in the Faculty of Aerospace Engineering changed from a semester system to a dimester system back to a semester system. However, the lament of the scientists that managers are in charge, dates back much further than this.

In 1992, Schijve and Vogelesang published an article in *De Ingenieur* [The Engineer], the journal of the Royal Dutch Society for Engineers. In this article they questioned the changing climate in the university. In their view, too much energy was absorbed by secondary things, whereas in a university of technology technological research should get fresh support. In line with



C-scan setup used in Structures and Materials Laboratory in the early days.



Current C-scan inspection setup.

the practical nature of their research, they emphasised the most important aspect of Delft's role in engineering and education: the creation of engineers. Engineers ought to be qualified problem solvers, capable of gathering information and able to think clearly about new concepts. According to Schijve and Vogelesang, "research develops better with less interference". In their opinion, people who were not knowledgeable about the future of education had too much of a voice in the debate. In the Netherlands a reduction of the university curriculum from five to four years, introduced in the 'classical' universities during the 1980s, was then under discussion also for technical studies. This was indeed implemented, only to be changed back again to a five-year curriculum a couple of years later. This shortening and extension was done as an 'accordion', without changing much in the curriculum. In the eyes of Schijve and Vogelesang, much of the debate on the curriculum was management talk. For scientists, these conversations hardly contained relevant information. It seemed as if the university had been handed over to the fashion of the day. A different organisational structure did not, as such, guarantee quality of research. The new managerial structures introduced financial controls by dividing the money for research into different programmes. Schijve and Vogelesang found that this led to such a high managerial burden for the researchers that they hardly had time to do their work. In that period, one of the new fashions was to set up interdisciplinary or inter-university units of research groups in so called 'research schools'. This repertoire of co-operation between different groups, to which interdisciplinary research centres were later added, had to be supervised by Delft University or the ministries of education and of economic affairs, who were in charge of the top institutes. However, in this way researchers were isolated from their faculty to become part of virtual units. Schijve and Vogelesang stated that continuing unrest and reorganisations created frustrations for researchers. Much ado about nothing replaced scientific concerns. It became fashionable to look at American universities as a kind of benchmark to be copied. The experience of Schijve and Vogelesang in their development of Arall and Glare was that industry preferred the approach of Delft, which was envied and often set as an example for American universities. "Instead of becoming academics producing articles to be stored in libraries and quoted by other scientists, as was common practice in many universities, let us concentrate on the real issues" was their message.

Boud Vogelesang presenting Professor Schijve the conference book.

Other industries

From the 14th to 15th of October 1992, a specialist conference was held in Delft on the Fatigue of Aircraft Materials and Structures in honour of Professor Schijve's retirement. On the 9th of June 1993, Vogelesang gave his inaugural lecture to mark his professorship, as Schijve's successor. In this lecture Vogelesang again added to the debate on the role of a university by unveiling his own concept for the laboratory of a technical university: the 'academic shop floor'. His inaugural lecture attracted a lot of publicity. At that moment he was in the middle of a pilot project with the Dutch Association for Small- and Medium-scale Enterprises (KNOV) to investigate how the high-tech knowledge of the university lab could be applied in those small firms that are not usually active in research and development. This was reflected in his lecture.

Vogelesang maintained that direct co-operation between industry and university would be as beneficial for the education of engineers as for the industry. He proposed a new concept for a university lab: "It should be a kind of academic hospital, a realistic working environment for the students during

the last phase of their study." He therefore called this concept the 'academic shop floor'. On this shop floor, industry and universities should co-operate and the students be educated to become real engineers. Vogelesang professed to be worried about a university education, which creates robots, taught to perform a set of tricks, but without practical experience. On his envisaged academic shop floor, the engineer should again become a designer, a creator of technical objects, instead of a theorist and academic. His comments were timely; the curriculum was then being shortened from five to four years and engineering education was in a crisis. Students no longer received any hands-on experience, because this was deemed too expensive. Instead, they got theoretical assignments and spent whole days in front of their bleeping computer screens. He argued that an engineer should be a problem solver with a real feeling for reality. The prime task of a technical university is not to educate scientists but to educate engineers. They need a helicopter view instead of tunnel vision. It goes without saying that not everybody was applauding Vogelesang's vision. Because the number of aerospace companies in the Netherlands was limited, Vogelesang's views implied a reorientation towards the non-aerospace sector, which was criticised by the National Aerospace Laboratory NLR. Besides, the competition between scientists and engineers at a technical university is always fierce, and the more scientifically minded researchers did not appreciate Vogelesang's ideas. The plea to use the university lab facilities to benefit industry was also a stumbling block for the Dutch technological institutes. They feared unfair competition because the university could use cheap labour, i.e. students. Students, with their motivation and fresh minds, are indeed important assets of the university. Nonetheless, Vogelesang's speech had a stimulating effect on the ministries of education and of economic affairs. His views could stimulate the 'production industry', which faced difficult times since the Dutch economy appeared to be gravitating towards transport, logistics and services. According to Vogelesang, intermediate institutes should be created between the academic shop floor and society, such as the Adhesion Institute that already existed, the Centre of Lightweight Structures, which was under consideration at that moment and later became a reality, and a Centre of Competence for Fibre Metal Laminates, which was eventually founded in May 2001 to act as an interface with the industry. These institutes needed to ensure the transfer of knowledge, while also playing a role in the acquisition of research contracts. He also foresaw a more theoretical institute for

computational mechanics, which became a reality through the later co-operation with Professor de Borst. It is clear that Vogelesang's ambition went further than the application of Glare. It was embedded in a vision of what research at a technical university ought to be. Vogelesang claimed in his lecture that his lab had a lot of knowledge on its shelves that was simply waiting to be dusted off and then applied in industry: "The university is a sleeping giant." This is especially true for long-term developments, which are too risky for industry. Vogelesang's lecture indicated the end of the way the aviation infrastructure had been organised since the war. As explained in the first chapter, Delft had originally only been given the role of educator of future Fokker employees and not asked to serve as a research institute for the industry.

Vogelesang's lecture also opened the door for contacts with the non-aerospace sectors. In 1992, for example, the Adhesion Institute started a large project to assist in the restoration of the 'Mesdag Panorama' painting in The Hague. This is a huge canvas – fourteen metres high and 120 metres in circumference – done by the Dutch painter Hendrik Willem Mesdag around 1880, which offers a sweeping panorama of the sea coast with the fishing village of Scheveningen. Vogelesang's lab engineered the woven reinforcement necessary to prevent the painting from tearing. The project certainly resembled the way in which cracks were stopped by fibres in Glare, but this was most definitely a very different field from aircraft. Tests were done to prove the durability of the repair and calculations made to prove that the shape of the painting would not be changed by the extra weight of the reinforcement. Queen Beatrix of the Netherlands was asked to unveil the restored painting when she was in the lab on the occasion of the graduation of her son from the faculty of Aerospace Engineering. She later did so on the 30th of October 1996. Vogelesang illustrated the viability and strength of his views with this type of innovation, culminating in the recent European successes in the development of Glare with the partners of the Airbus consortium.

Vogelesang mentioned in his lecture the need to include elements like care for the environment, and ethical, historical and cultural aspects in the curriculum – and in the development of new technology. In a way, this book is the result of his vision for the relevance of history. With Professor de Jong, he gave me the opportunity to work on those aspects and to include and teach History of Technology and Ethics of Engineering in the curriculum. It also became part of the development of Glare. The importance of this was

highlighted when Erik Tempelman, who joined the group as a student in 1993, did a preliminary thesis on the ethics of the application of new materials in aircraft structures, certainly a special subject in the lab. Tempelman had strong feelings about the responsibilities of engineers towards society at large, and his position in the Glare group reflected Vogelesang's own views on this subject. Tempelman did his Master's thesis work on sustainable development and the recycleability of the Glare material.

He studied the environmental impact of aircraft – increasingly important these days – and proved that Glare is able to significantly reduce the strain on the environment. Although recycleability is of secondary importance for aircraft materials, he proved that the aluminium fraction in Glare can be separated from the prepreg fraction in an economic way. Tempelman continued this work for transport structures in general, in co-operation with the Faculty of Technical Earth Sciences in view of its knowledge of recycling. He and I worked together to give lectures to the students of the materials group on the cultural aspects of technology. Since the aerospace community was under increasing pressure from the media and the government to reduce aircraft noise and engine exhaust emissions, due to its enormous growth, this was a timely subject. New technological developments urged engineering educators to include ethics in the curriculum. The stressful work involved in developing Glare did not absolve the researchers of this responsibility. It was felt that it was necessary to reflect on the wider implications of the use of Glare. Lighter aircraft would imply cheaper airfares, which would stimulate further growth of aviation, by which the positive effects of the light structures on fuel consumption would be neutralised. This is called the 'rebound effect'. Insight into the mechanism of the dynamics of society could place the role and responsibility of the engineer in the right perspective. However, this mechanism is certainly much more complex than the phenomena involved in the design and manufacture of aircraft. Evidently a much longer time would pass before changes would be felt.

Airbus

In his inaugural lecture, Vogelesang described to the students the Greek myth of Sisyphus, who had to perform endless and meaningless

labour of rolling stones uphill. He urged them in this way never to give up. The development of Glare in this period certainly seemed to be comparable to Sisyphus' labour. The runway appeared endless. However, the willingness to consider the application of Glare, as well as the personal relationships with Airbus engineers and managers, appeared to be more promising than those with Boeing. Airbus Industrie had from its conception a stronger incentive to implement new technologies than Boeing, which could rest on its laurels, striving only for consolidation of its market leadership and further cost reductions. Airbus Industrie also suffered from a significant handicap, as it was a consortium of independent partners: British Aerospace in the U.K., Messerschmitt Bölkow Blohm (MBB) in Germany, Aérospatiale in France and Construcciones Aeronáuticas S.A. (CASA) in Spain. In practice, the partners not only co-operated but also competed with each other to produce certain parts of the aircraft at the same time. Their cultures and know-how also differed. Fokker was not an Airbus partner, but produced some parts for Airbus aircraft. In 1990, in the middle of the change from Arall to Glare and during the fight between AKZO and ALCOA, a meeting was held at Aérospatiale, the French partner in Airbus Industrie, to discuss the results of fuselage studies with Glare. Johannes Koshorst from the headquarters of Airbus Industrie in Toulouse, who was responsible for co-ordination and stimulation of material developments at Airbus Industrie had initiated these studies. In March 1989 he granted a contract to Delft and to the French manufacturer and Airbus partner Aérospatiale to carry out this work on 'R-glass Arall', as Glare was still called in those days. Koshorst had already funded some work on Arall at Airbus in 1982, after a visit to Delft where he had contacts with the composites group and where he happened to meet Vogelesang. The project on R-glass Arall was a follow-up of the project on Arall, of which the results were shown at the second specialist conference in Delft in 1988. The results on this fuselage study for aramid Arall had been disappointing. It only indicated an eight percent weight reduction against an eight to tenfold price increase. This was certainly not acceptable.

Fortunately, Glare was introduced shortly afterwards and this material was immediately considered to be more promising. In 1989, the results of the new R-glass Arall studies were presented and discussed. At one of these meetings, bicycle tubes made from Glare were passed around, which helped to build confidence in the endless possibilities of the new material. The stream of research from the students at Delft helped strengthen the case and light the spark of enthusiasm. The possibility was discussed of

producing the material in Europe, and because of the fight at that time with ALCOA it was reasonable to look for a production site at Fokker. At the meeting in June 1990 called by Airbus Industrie and all its European partners to discuss the outcome of the fuselage study, the Glare fuselage option for the Airbus A320 appeared to lead to a 25.9% weight reduction for a $280/kg saving. This was very promising compared to the disappointing study with the Arall fuselage. Fokker worked very hard on research and development for fuselage applications in these years and was the best customer of SLC. Stimulated by the NIVR, which funded co-operative research as an extension of the F-27 wing panel project, co-operation between Fokker and Delft improved.

The fuselage study on the application of Glare for the A320 was carried out by Buwe van Wimersma, Wim Slagter, Rob van Oost and Koen Zaal, all Delft graduate students, under the supervision of Gunnink. Slagter and Zaal started a PhD-study after their graduation, while Van Wimersma joined SLC. In the same period that Van Oost was studying Glare at Boeing, Van Wimersma went to Aérospatiale in Toulouse to study the feasibility of using Glare in the Aérospatiale parts of the Airbus aircraft. Within the Airbus consortium, every partner was responsible for their own section of the aircraft, tending to create a patchwork of different technologies, which needed harmonisation. There were also ‘border disputes’: for example, in one case a structure in the section assigned to one of the Airbus partners had to be supported. The optimal solution was to incorporate a support in a section produced by one of the other partners, but this proved impossible, and a sub-optimal solution had to be chosen within its own part of the structure.

In Airbus, each partner had its own focus. The British designed and produced the wings, while Aérospatiale was responsible for the complex cockpit and for the centre section of the fuselage. MBB was responsible for the rest of the fuselage and CASA for the tail.

Initially, Aérospatiale studied Glare with some reservations. Its aim was to keep up with the German Airbus partner MBB, later renamed DASA, DA, DCAA, and currently, since its merger with Aérospatiale, EADS Germany, part of the trans-national European Aeronautic Defence and Space company (EADS). Clearly the university organisation was not unique in its constant revisions. The aerospace companies also underwent a wave of reorganisations and mergers.

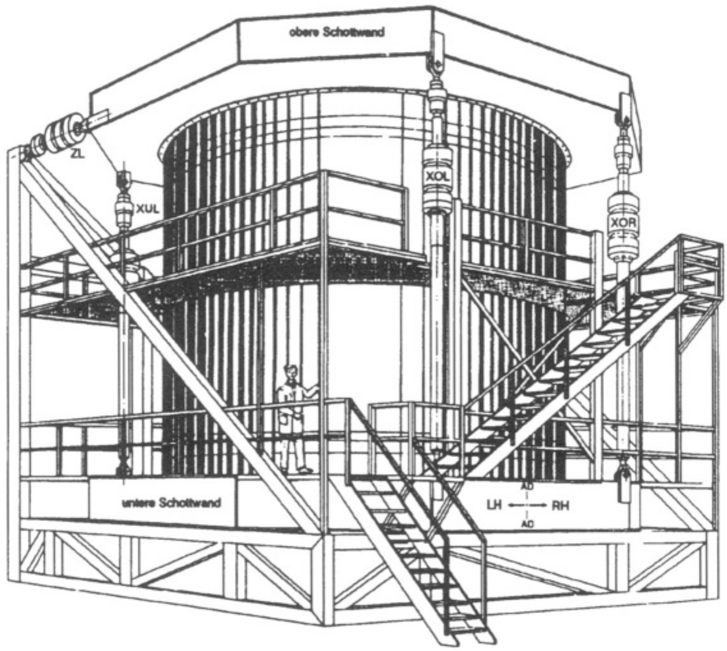
Barrel test

If the French were somewhat reluctant to study Glare, the Delft researchers found the Germans to be more receptive. A Dutch-German relationship developed around Glare that would be essential for the final success of the material. It dated back to 1988 when MBB engineer Nicolaus Ohrloff found an article on the material of Vogelesang in a journal. The article stressed the extremely slow crack growth rates and the switch from Arall to Glare. Ohrloff showed it to his colleague Thomas Beumler. They became interested, phoned Delft and were soon to be found testing Glare riveted joints in Hamburg. Just at that time a segment (called a ‘barrel’) of the Airbus A330 and A340 aircraft fuselage was planned to be fatigue tested for certification in Hamburg. There was sufficient money for testing at that time. The full-scale article to be tested should include a cargo door, which would typically be used in the freighter version of the A340. A barrel was planned to support work on the associated passenger section. Later the freighter was cancelled and the full-scale test article was designed for the passenger version only. Since the budget was already allocated, the barrel segment became available for research purposes. The advantage *and* disadvantage of a big, sometimes inflexible company like Airbus is that, once money is allocated, it will be used for that purpose even if the targets have changed en route. It was the task of Ohrloff and Beumler to define the barrel test. They decided to study the application of new materials, including two aluminium alloys with lithium, the common fuselage alloy 2024 as a reference and the alloy 6013. Two upper shells, called the ‘crown section’ of the fuselage, the part of the fuselage with the highest tension load, were available for fibre-metal laminates. In the way that the F-27 wing panel project was the essential first proof of the pudding for Arall on wings, this opened up the possibility of the first realistic test on Glare for fuselages.

First there had been plans to test Arall on the barrel but MBB decided to withdraw it from this test. Schijve, Vogelesang and Gunnink sent a letter to the company with a plea to test R-glass Arall instead. They considered it to be important for the European manufacturer, since the U.S. was still interested at that moment and Europe might otherwise be left behind. Their efforts were successful and Glare was accepted. In 1988, Ohrloff and Beumler, together with Professor Schwarmann from Bremen, drove to Delft for the first time. Professor Schwarmann, who worked for MBB on damage tolerance methods and handbooks, was a good friend of Schijve. In Delft

they had a meeting with Gunnink in his small office on the ninth floor of the Aerospace Building to discuss the possibility of obtaining Glare panels for the barrel. In Delft, the German engineers encountered the same non-bureaucratic culture and the same way of working as in their own department in Hamburg and Bremen. Ohrloff and Beumler were used to a situation in which they could challenge the rules of a big organisation, and in which everybody was interested in new work. They could take a piece of material, walk to the machine shop to get specimens more and then walk to the test office to execute the tests, without too much paper work. Ohrloff was interested in the material but foresaw the enormous difficulties they would encounter on the road towards acceptance of the material within MBB and the gigantic Airbus consortium as a whole. Beumler, an energetic man who relished such challenges, became one of the main boosters supporting the development and application of Glare. A dedicated engineer and organiser, he even spent a lot of his free time at home working on Glare.

Thomas Beumler.



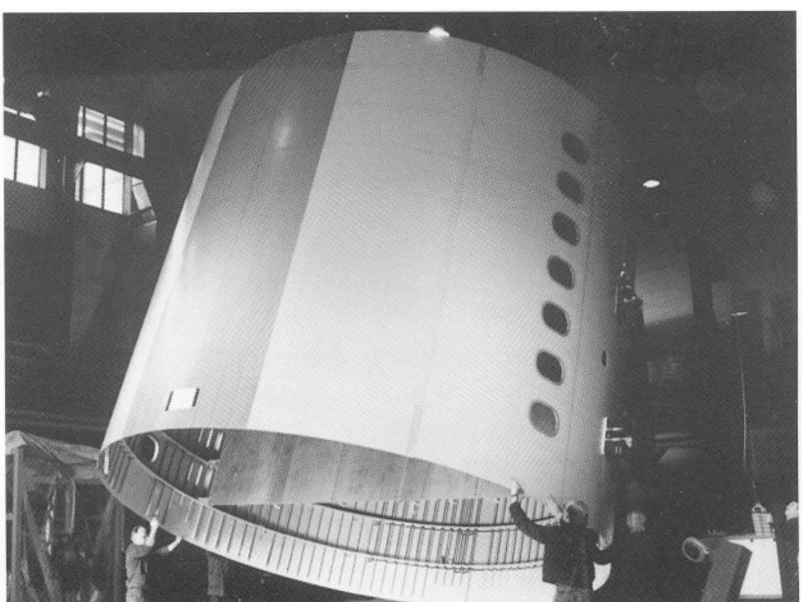
Schematic overview of the barrel test setup.

The good news for Gunnink was that Glare had made it as far as this important test. The bad news was that they only had eleven weeks to deliver the material. Gunnink contacted Verbruggen about it. The Germans needed five-metre long panels, which had to be produced at Fokker since AKZO was not on speaking terms with ALCOA at that point. AKZO had already initiated talks with Fokker for a production site for Glare. Six sheets were produced for the barrel at Fokker’s Schiphol plant, which cost AKZO the enormous sum of 180,000 Dutch guilders.

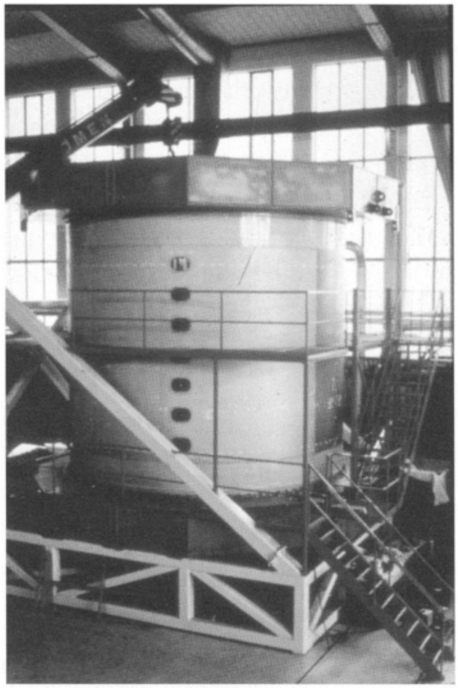
However, things did not go smoothly. The prepreg was still not fully optimised and defined after the break with 3M, and a brittle adhesive was used which could lead to disappointing results when the barrel was tested. Roebroeks was holding discussions with the producer Ciba Geigy in the U.K. for the adhesive and with Vetrotex in France for the right glass fibre.

During the production many problems had to be solved with the primer, which did not adhere properly to the pretreated aluminium sheets. Nonetheless, the Glare material was the first of the various materials to be delivered to MBB for the barrel test. In 1990 the fatigue test on the barrel

was started. It continued until 1994 and was finished after 100,000 flight cycles. Each week one thousand cycles could be applied, after which the barrel was inspected for cracks, which took another week. After the fatigue tests, artificial damage was applied and tests of the residual strength were performed. The in-house tests that were conducted by an important Airbus partner who was responsible for a large part of the fuselage was a great success for Glare. The material was tortured with hammers to produce dents, saws were set in the material to create cracks and milling machines were used to remove the outer aluminium layer to simulate corrosion damage. The residual strength of the material in the presence of these types of damage was a big concern at the time, since it was found to be lower than that of the 2024 aluminium alloy. PhD-student Coen Vermeeren therefore concentrated on this topic, as did Professor Schwarmann at Deutsche Aerospace. It was a possible showstopper for the Glare material. In Delft everyone held their breath, because they knew that the prepreg used in the Glare panels was not optimal. Glare survived all this, while all the other materials on the barrel had to be repaired after significant crack growth.



The test barrel as it is being placed in the test setup in Hamburg (Glare section is visible due to its darker colour).



Full-scale barrel test in Hamburg.

Other tests

Apart from the barrel, Beumler also initiated other test work. In the full-scale fatigue test on the A320, cracks were found in the circumferential strips ('butt straps') that connected the fuselage sections. Since this strip is located inside the aircraft, it is difficult to inspect for cracks. Because the design of the aircraft was already finished, a material was needed that could replace the original strip without necessitating changes in the rest of the structure. Glare was an excellent candidate for this, although titanium was also an option. Since Glare still was not qualified as a material, a special part qualification programme was needed for the butt strap that would cost 2000 man-hours. The programme management of the A320 was not sufficiently interested to spend the money, although successful tests were done by an undergraduate student in Hamburg and in Delft on realistic specimens with a butt strap connecting two pieces of skin. Another Delft student did computer calculations on this detail with Glare. Delft's formability expert Jos Sinke

developed methods allowing Glare to be able to produce the required complex shape of the connections of the stiffeners over the butt strap. Sinke continued to work on the manufacturing aspects of Glare, which would become essential for the later application of the material on the A380. Since this problem also affected the French section of the fuselage, Aérospatiale was also considering Glare. The French were still not very enthusiastic about the material and finally it was decided to stick to the original design in aluminium and just to inspect the butt-straps more frequently to ensure that possible cracks would be found in time.

Jos Sinke (right) and Michel van Tooren (left) preparing a sheet metal forming test.

In the early 1990s a large reorganisation aimed at cost reduction was taking place in Germany at DASA under the name 'Dolores', and a lot of employees were forced into early retirement. As a consequence of 'Dolores', the budget for new development was cut and the work on Glare slowed down considerably. Suddenly there was no money available for the qualification of the Glare material. However, the good results from the Glare parts of the barrel were now available and Beumler managed to keep the development alive by getting a Glare part on the full-scale fatigue tests of the

A340. For this aircraft, a bulkhead section at the rear of the fuselage was designed and manufactured in Glare. Koshorst financed this project from Airbus Industrie via SLC, which had to produce the necessary parts. The rear pressure bulkhead is a curved shell, which closes the pressure vessel of the fuselage and is vital to the aircraft. Yet the rear bulkhead is difficult to inspect because it is hidden by installations, toilets and galleys.

Damage tolerance of this part was high on the agenda since a couple of years earlier a bomb had exploded in an A300 toilet situated next to the bulkhead, damaging it considerably. Although the aircraft had been able to withstand this damage, the incident had created an awareness of the essential level of damage tolerance of this aircraft part. Secondly, possible ways to save weight are an issue for aircraft engineers at any time.

The Glare section produced for the bulkhead was the first Glare part that was manufactured and tested with a curvature in two directions. The three separate 0.3 mm aluminium sheets were stretch formed together in Deutsche Airbus' Nordenham plant before bonding them together by placing the intermediate prepreg layers in between the formed aluminium parts. This procedure was unavoidable, since the minimum radius of the bulkhead is no larger than 800 mm. Later, in 1996, double-curved Glare was produced by laying up aluminium sheets in a double-curved mould without preforming and by using splices to prevent excessive wrinkling of the sheets and autoclave pressure to press the sheets in the right contour. Student Van Oostrom did the first production trials in this way in 1996. The stretch-forming process is very expensive. Bonding of the pre-formed aluminium sheets into Glare took place at a specialised company in Los Angeles. Although highly contoured, a splice had to be included, which allowed the part size to be increased by 50% compared to the baseline. At another location in the bulkhead, three radial crack stoppers in titanium were replaced by stoppers made from Glare. Although the tests again proved the excellent properties that had already been found in Delft on small coupons to be valid for realistic structures, the chicken-and-egg situation of no application without qualification and vice versa was not broken. Enthusiasm was still limited to the engineers, while the management remained sceptical. However, important experience was obtained in this way.

Sometimes results were not immediately favourable for Glare. For example, it proved extremely difficult to produce a bulkhead attachment. It took a lot of belief to trust that some real aircraft parts could be constructed out of the aluminium sheets that came out of the Glare forming process

looking like wrinkled handkerchiefs once more experience was obtained with the production process. Without the shielding environment of the university, where it was always possible to look for innovative solutions, a new technology like Glare would never have grown up. Had Glare been developed in the highly competitive environment of a big aircraft company like Airbus, the idea would have been discarded as impractical long before. Competing groups are always willing to attack the technology on the basis of unexpected results. The fight was certainly not an easy one and the Glare technology needed some protection, especially in the early days. A new development is never without disappointments that have to be solved. The basis of the Glare support in terms of the engineers that were familiar with its properties and who backed the material remained small and the support of higher management levels would be needed. In DASA, Beumler managed to neutralise all internal attacks against Glare, but in fact he was just a member of the fatigue and damage tolerance department. It was not his task to develop a new aircraft material but to do fatigue analysis on existing ones. Yet the freedom and flexibility of the culture of the department made it possible that someone could take up this challenge. One of the problems with Glare was that there was actually no department that could take Glare under its wings. The aircraft materials groups were divided in two camps: one that promoted carbon composites, and an aluminium group which was busy with the new aluminium alloys that were developed as a response to carbon. As we mentioned in the previous chapter, ALCOA had developed a new alloy and was expending a lot of effort to make it a commercial success. The Glare material had no clear position in this competition between aluminium and carbon. For the aluminium fans it was a composite and for the carbon promoters it was an unclear compromise. The result was also that the development work on Glare in Germany and in Delft did not fully cover the required scope of different aspects.

Since a co-ordinated effort to adopt the material was lacking, the test work that was done was not always defined by the specialist who had to be convinced. Some aspects did not receive the proper attention that was required because not all the necessary questions were asked. Not all aspects could be covered by Delft; the strength of the Delft staff was that they were generalists who were able to bridge the various disciplines required for the application of a new material. A specialist would not be able to accomplish this. However, for the material to become a success, the various specialists at Airbus also needed to become involved. Within Airbus,

the number of people that were involved was too small to ask all the relevant questions. In Hamburg, it was expected that Delft would take the lead and vice versa. This resulted in the fact that after all the initial work in Delft, Hamburg and Toulouse had been completed, a large number of uncertainties remained to be covered to close all the technological gaps. The main emphasis was, however, to keep the Glare development alive and to strengthen the case for the material in such a way that it could be seriously addressed. This would gradually happen in the course of Glare's application in the Airbus A380, which is outlined in the next chapter. The durability of the material was just one example of a problem that was not completely treated in this period, since it was not possible to determine the best way to get a handle on the subject. The long-term behaviour under influence of moisture and changing temperatures and under realistic loading conditions over 25 years of aircraft use is difficult to simulate in a lab. However, a convincing set of evidence was needed to create confidence that Glare would withstand realistic conditions. It took negotiations with all the specialists to develop a test programme that could be considered realistic.

In 1994/1995 Roebroeks carried out tests which created a lot of anxiety in Delft. Significant strength reductions – of the order of thirty percent – were found after exposure of Glare to a high humidity environment. Roebroeks discovered that this effect is characteristic for *small* coupon specimens, where the moisture can penetrate through the whole width. In contrast he found that the US Navy's experience with *large* glass fibre-reinforced structures, when examined after twenty years of service, showed that no degradation had taken place. Roebroeks reached the conclusion that in real structures only the edges of the laminate are affected and that not only periods of high humidity will occur but also dry periods in which the moisture evaporates out of the structure. This indicated that the accelerated lab tests on small pieces of material were not relevant. However, these tests are standard for composites. It was the first serious drawback for Glare, and although the story was convincing it certainly required a positive, realistic mind set.

The flexibility in the department in Hamburg certainly played a crucial role in this stage of the development of Glare. The positive results gradually created trust in the technical soundness of the material. Many smaller tests were done in Hamburg and a lot of experience was gained with the new technology. In this period, from 1992 to 1996, a second project involving a number of aircraft companies in Europe got under way, sponsored by the

European Union under the name Brite Euram project BE 2040. Participants in this project were: Fokker, Deutsche Aerospace Airbus, British Aerospace, Aérospatiale, Dassault, Dornier, DASA, Structural Laminates-bv, NLR, DLR, TU Delft, TU Braunschweig, Alenia and CASA. In this way, other European manufacturers also gained experience with the material. Although the project did not really develop Glare further and repeated much of the work that had already been done in Delft and Hamburg, it did help to spread knowledge and experience with the material across Europe. The contact and exchange between the different companies in such a European project was valuable, although it did not lead to real co-operation because every partner tended to pursue its own interests and expertise.

U.S.

Although Boeing discontinued its association with Glare, the connection between Delft and the U.S. always continued. It is hard to imagine any development in aviation without involvement from the United States. On the one hand, Airbus feared any flow of knowledge across the ocean, while on the other hand the company would be surprised if no interest was shown. The technology for Glare applications had to be guarded, but Airbus realised that a technology can only be successful if widely applied. Rob Fredell, a US Air Force officer who had already worked on Arall and was present on the first Arall conference in 1987, started his PhD-study in Delft in 1991. This was quite unique, since American officers usually did their PhD-work in the U.S. In Delft, Fredell started a project on repair and managed to gather a large group of undergraduate students for his team. His research focussed on the possibility of repairing existing aluminium aircraft structures with bonded Glare patches, comparing the results with the conventional composite patches that are applied for these purposes.

He discovered that because of the smaller thermal mismatch between aluminium and Glare compared to the combination of aluminium and composite, the Glare patches behave better. This initiated a lot of work on bonded patches for several years in Delft and when Fredell returned to the US Air Force Academy he continued his research there by hiring two Dutch graduates, Kees Guijt and Stephan Verhoeven. They remained the Glare bridgehead in the U.S. and brought a special Dutch flavour to the

highly bureaucratic US Air Force Academy by introducing the characteristic Delft culture and humour. This repair project even led to the fact that the first Glare application to take to the air as part of a primary structure was achieved in the U.S.; in October 1995 a bonded Glare repair patch was installed over cracks in the fuselage of a gigantic C-5A Galaxy transport aircraft. The repair project drew a lot of international attention, which helped to keep the world's specialists interested. The repair project was also continued in Delft and later another PhD-student, Arjan Woerden, started to work in this area. Another American project was for the US Navy, in co-operation with Drexel University. From 1992 to 1994, research was done on special high temperature laminates for supersonic transport, which suffer from aerodynamic heating. On the Dutch side Coen Vermeeren did the work on this type of fibre-metal laminates. As a follow-up to this project, the NIVR sponsored a project, carried out by Kees Guijt, on high temperature fibre-metal laminates for space applications consisting of thin layers of titanium and special adhesives reinforced by carbon fibres. This high temperature variant of fibre-metal laminates is currently still under development.

Broadened outlook and focus

The co-operation between Hamburg and Delft was intense and far more fruitful than the relationship that had existed with Fokker. Information was transferred quite easily back and forth. The culture of the Germans matched that of Delft very well and the engineers on both sides enjoyed the exciting work on the new material. What was still lacking, however, was a trustworthy industrial partner who was willing to share the risk of producing the Glare material. SLC, with AKZO and ALCOA in the background, was a real industrial partner. The dedication of SLC employees like Bill Evancho, Jim Thomas, Carl Gareshé and Marc Verbruggen was vital for the success of the Glare project, especially for the development of a smooth and mature technology from what was still essentially a laboratory process, and to establish confidence in the material. One could depend on the material deliveries from SLC, which was of the utmost importance for DASA. However, as we have seen in the previous chapter, AKZO did not have the experience in the aerospace sector and ALCOA was retreating from its initial enthusiasm for the Glare material. In the aerospace business, the subcontractors usually take part of the risk of developing the aircraft and

therefore long-term industrial alliances had to be built in a different way than AKZO was used to in the bulk chemical sector, which was its core business. Airbus wanted to be sure that Glare would be available for the next thirty years. In 1994/95 the ‘Dolores’ reorganisation took its toll and the work on Glare came to a virtual stop in Germany. Nonetheless some Glare repairs were tested on the barrel and co-operation was taking place with a PhD-student from Delft, Richard Müller, who was studying the behaviour of riveted joints in aluminium and Glare fuselages. Since those riveted joints are usually the critical location where fatigue cracks start to develop, this was very important work. Müller established a database of test work on joints, which proved to be essential for the understanding of the behaviour of Glare joints. Like the other PhD-studies, it was an important piece of the puzzle that was being assembled to show a complete picture of the Glare technology. The PhDs contained the results of the undergraduate students who did their Master’s theses and who were usually guided by one of the PhD-students. Numerous Master’s thesis projects were done in this period. However, around 1995 it appeared that some further action was necessary in order to prevent the Glare project from fading away in Delft. Students are attracted to projects that are new and fascinating, but after so many years it was difficult to keep the same enthusiasm and flavour of novelty as in the beginning when everything was new and fresh. As we saw in Vogelesang’s inaugural lecture, the university staff also broadened their outlook. It was felt that Delft had a responsibility in the Dutch industrial context and that it would be wise to avoid placing all the bets on Glare. The future of the research group should not depend on the application of one material. On the other hand, Glare offered excellent possibilities for scientific study on physical properties, to do modelling work, and to expand the knowledge base in a way that was also fruitful for other materials. Glare functioned as a kind of stepping stone for general research on different properties. Müller’s PhD-study, for example, was on riveted joints. This ancient technology was already in use by the ancient Greeks and was applied from the start in aluminium aircraft structures, but his study on Glare revealed that a lot was also still unknown even for aluminium, despite all the experience with the technology. The findings of his dissertation were taken up by Airbus in Germany for aluminium before Glare was applied. Therefore, all the efforts of the university group on Glare would certainly not be in vain. The work had led to an increase in knowledge and experience in the behaviour and modelling of aircraft materials, which was useful in general. What also

played a role in the changing situation was that the success of the group in Delft led to growth. An Adhesion Institute was founded and also a Centre on Lightweight structures. The Glare project became one amongst many others. All these projects were carried out in the lab and the group of people working in the lab was expanding rapidly. This also put the culture of friendship and personal relationships around the coffee table to the test. Delft entered a new period.

Richard Müller and his barrel test setup.

France

Van Wimersma was sent to Aérospatiale by SLC for support in 1994. As a skilled designer, he was able to create a place for himself within the company, even as a foreigner from another company. He started a design study for the application of Glare on the A330 fuselage as a follow-up to the previously successful A320 study that he carried out as an undergraduate student. Although the outcome of the A330 work was quite positive and

indicated a 20% weight saving, the French remained sceptical and reluctant. The difference with the situation in Germany was that in France, Glare was in the hands of composite specialists who considered carbon to be the way to go. In their opinion, Glare could at best only be a step between aluminium and full carbon composites. In the composites department, the assignment to work on Glare meant a dead end to your career. Five or six French Glare designers responsible for Glare passed by over the years and every time Van Wimersma had to start all over again with the 'education' and by creating goodwill. "Glare, à la mer" was the popular saying and the fact that the sound of Glare in French was not so shiny as in English, resembling the word 'glaire' (phlegm) in the French language, did not improve matters. "Who wants to make an aircraft of phlegm?", was one of the jokes he became all too familiar with. Once Van Wimersma accompanied one of his French colleagues, who was responsible for Glare, in a car. While they drove past a churchyard, his colleague quipped: "Look, there is the spot we reserved for burying Glare!" It left Van Wimersma feeling uncomfortable. All the same, the French had to be involved in Glare to keep up with the developments in Germany where progress was fast. In Germany, design studies were done on upper shell panels of the A340 fuselage, which indicated a possible weight saving of 14-17%.

In France the opinion on Glare remained critical. Most of the development effort was put into carbon composite aircraft parts, since this was considered to be the future. In a way, the scepticism made sense since Glare had to be considered as a modified bonded aluminium structure and not as a composite material. On the other hand, the French criticism and their experience with composites also helped Glare. The French critics scrutinised Glare rigorously. The Germans discovered the French to be excellent sparring partners. The presence of different nationalities in Airbus was therefore also a significant asset. It was important that Aérospatiale carried out the first serious cost study on the application of Glare in the A330 aircraft. As a material, Glare was 5 to 10 times more expensive per kilogram than a traditional aluminium alloy and this was an important barrier to overcome. Boeing had never got past it and everybody could use this figure to rule out Glare easily because in the end each beautiful technology has to face economic reality.

Because Glare leads to weight savings, less material is necessary, but this will not close the gap between the aluminium and the Glare structure. The remainder has to be balanced by the reduced operating cost

because of the reduction of fuel burnt due to the lighter structure. However, cost reduction during manufacture was a prime issue. The era in which the application of new materials was performance-driven was over. For the material to be viable, the cost of the Glare structure had to come very close to the aluminium structure. Delft considered this to be possible because the excellent fatigue properties of Glare can make an aircraft structure in Glare simpler than in aluminium. For an aluminium structure, reinforcements have to be added around joints in order to reduce the stress levels and prevent fatigue cracking, while this would not be necessary in Glare. Also the crack stoppers, which are necessary in aluminium because significant fatigue cracks may occur and adequate residual strength has to be assured, are not necessary in Glare.

In Glare, the reduction of parts reduced the production costs of the structure. At the same time the use of the so-called ‘splices’, which were invented at that time to produce large panels, was favourable to Glare, as larger panels imply less expensive joints. Because the maximum sheet width of aluminium was originally 2.5 metres, the Glare sheets had to be connected by riveted joints every 2.5 metres. Splicing meant that the sheets would be connected in the Glare internally by bridging fibre layers and by adding extra aluminium sheets. The limit of the size was now the size of the autoclave, but they were huge. However, all these advantages were never quantified and the cost of the Glare material was still considered by many Airbus engineers to be the main obstacle to application. An extensive cost study which was performed by Aérospatiale with the help of Van Wimersma on the application of Glare on the A330 fuselage indicated that although the material costs of Glare are high, the total, finished cost of a Glare product comes very close to an aluminium product. This definitely proved that Glare should not be produced as a sheet material that has to be shaped and machined into a product as is the case for aluminium, but that Glare has to be produced as a component. It had to be laid up and cured in a curved mould such that after curing a product came out of the autoclave with the right shape for the specific aircraft, including the right local fibre orientations and reinforcements that are necessary. In this way, the number of production steps could be reduced significantly. This layup and curing resembles the much earlier way that Fokker had produced his plywood wings and also the production of the wooden fuselage of the Mosquito by De Havilland. Despite the fact that the French added a lot of extra factors to the cost to include uncertain aspects, this conservative approach led to a positive result for

Glare. Unfortunately the A330 cost study on Glare was never signed and released as an official document by Aérospatiale, probably because the outcome was so unexpected and striking that the senior management was not willing to take the responsibility for it. For the Delft team, however, it certainly was a pleasant surprise.

Van Wimersma's co-operation with Aérospatiale was nevertheless very intensive and the criticism had proven to be the stimulus needed to achieve the best results. Working for SLC was very stressful in those days. The constant barrage of questions from customers like the French Aérospatiale and the German company DA called for satisfactory answers, since this was vital for the confidence that the foreign engineers had in the material. Each question had to be treated with the utmost seriousness since it could mean the end of the project. Every time a specific issue came up, or when some important work had to be carried out to convince people, all those at SLC dropped whatever they were working on and pitched in to answer the question. Material was produced, specimens were made, tests were done and reports were written in a time that beat records. Beumler had the impression that a hundred people were working in Delft with dozens of testing machines to produce all that work, but in fact the basis of the project in Delft remained relatively modest. The laboratory in Delft was always able to answer the questions since it was very flexible and therefore able to produce test results fast. Even Aérospatiale was impressed and actually invented a name for the Delft approach: 'real-time testing'. A question posed to Van Wimersma usually produced a test report within two weeks. Within the aircraft company, a fortnight was not even long enough to make a start on the paperwork to propose testing. Executing a test at Aérospatiale could take a year. The situation at SLC was especially stressful around 1995 because AKZO and ALCOA wanted to put less money into the company. A lot of money had already been spent and still there were no signs of a rapid wide-scale application of Glare. The Dutch Ministry of Economic Affairs had to provide a subsidy to keep the Dutch part of SLC alive. This was just enough to bridge the gap between the work done for Airbus and the growing interest within the company.

Toward a new era

This was also the period in which strong personal ties were established between Airbus engineers and Delft. Although those in Airbus involved in Glare could still be counted on one hand, they had proven in numerous tests the excellent properties of Glare. On the Dutch side, some important events took place. In 1994 Vogelesang and I started an interfaculty project in co-operation with the Faculty of Civil Engineering with Professor René de Borst, one of the world's leading scientists in the field of mechanics and the head of the Koiter Institute on Technical Mechanics. Two PhD-students started their work: the German Frank Hashagen, who would later go to EADS in Hamburg to work on Glare, and Tjerk de Vries, who would become one of the important project leaders within the Glare development for the A380 (dealt with in the next chapter). Through the connection with De Borst, who later became a professor at the faculty of Aerospace Engineering, Glare entered a new arena. Up to then, the Glare development had been focused on applied research. This was, as we saw in Vogelesang's eyes the most important focus of a technical university. With De Borst, a more academic tradition was brought to the Glare project and eventually it may become possible to understand theoretically why the behaviour of Glare is so excellent in aircraft structures. Through journal publications, Glare could also be introduced into academic circles, which for a long time stood aloof from the culture of the Delft group. As a research field, the work on Glare attained academic status.

Another important milestone was the first regular application of Glare in a primary structure of an aircraft. In 1996 Shorts of Northern Ireland, one of the companies that make up Bombardier Aerospace, decided to apply Glare for the forward bulkhead of the Learjet 45 business jet. Although this was a small structure, it was certainly an important one. Another Glare structure that took to the air in this period was a set of Glare stringers installed by the Indonesian maintenance engineer Soerjanto. He had been sent to Delft by his company, Garuda, for his PhD-study on the maintenance aspects of Glare. The stiffeners had to replace corroded aluminium stiffeners in the cargo bay area of an aeroplane used to transport seafood, which frequently dripped salt water on the structure. Since Glare is layered only the outer aluminium will corrode, after which the corrosion is stopped by the prepreg layer that functions as *a* corrosion barrier. Soerjanto also used a DC-10 as a test setup for his research by installing a Glare floor panel near

the door of a cargo bay at a location that is prone to impact damage. This unique opportunity to install Glare parts by someone who is responsible for a fleet of aircraft came at the right moment at the end of the initial material development of Glare. This in-service experience with Glare proved to be essential in the next episode of the Glare story.

In the same year, on the 15th of March 1996, the bankruptcy of Fokker ended the existence of a company that was once the pride of the Netherlands. It reflected the worldwide crisis in the aerospace business at that time. A German manufacturer, DASA, owned a majority share in Fokker and requested large sums of money from the government to be able to continue operations. However, the Dutch enthusiasm for aviation was no longer enough to keep Fokker flying. The Dutch Minister for Economic Affairs did not want to pump such large sums of money into the company anymore. The new belief in the liberal era was now return on investment. Parts of Fokker were sold to the Dutch machine producer Stork. The production of sub-assemblies was concentrated at the site in Papendrecht, the first location in the Netherlands where metallic aircraft were produced, as we saw in Chapter 1. The Papendrecht company was to be known as Fokker Aerostructures and was aimed at the production of aircraft sections for other companies like Gulfstream and Airbus.

For the Faculty in Delft, the impact was enormous, as it decimated the Dutch labour market for Delft graduates in the aerospace business. After the bankruptcy, Airbus contacted Delft to reassure them that its aerospace faculty remained important in Europe. The faculty managed to communicate to future students that the education they provided was aimed at the integration of high technology in various types of products and that the skills its graduates acquired were valuable in all kinds of industry. It also started to make more use of its international reputation by acquiring American accreditation and by forging industrial alliances, for example with Boeing and Airbus. Freed from Fokker, the faculty now became truly international in a world that was rapidly globalising. The message was clear and soon the faculty regained its position as one of the fastest growing technical programmes in the Netherlands. Faculty dean Professor de Jong, Vogelesang and the final success of Glare on the A380 super-jumbo – described in the next chapter – all played key roles in conveying this message to society. Evidently, the university had to play its role in a transparent way, as we saw at the beginning of this chapter.

In August 1996, the staff of the lab (Vogelesang, Vlot, and Sinke) and SLC employees (Gunnink, Roebroeks, Van Wimersma, Van Oost, and Van Hengel) had a meeting to discuss how to continue with the lab's involvement in the Glare project. After a period of strong involvement, the changed situation in the lab with its new diversity of projects had led to a situation in which SLC people increasingly had to carry most of the weight of Glare, functioning as a kind of intermediate between the university lab and the industries. This recognition was later formalised as the Fibre Metal Laminates Centre. A lot of students were still involved, but a new spirit had become necessary to give a focus to the wide variety of work that was being carried out at the lab. It was decided to set up an umbrella organisation to assure integration of the various aspects of the development of Glare. The Airbus project for an ultra high capacity aircraft, then known as A3XX, would serve as such. A student project was set up to help develop the Glare technology for this very large aircraft that would finally take the project beyond the threshold of the runway.

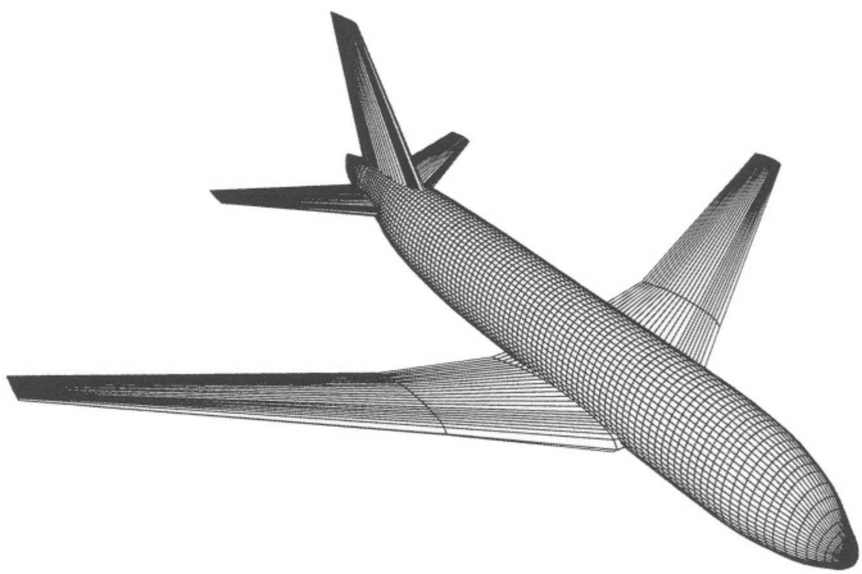
5

The end of the beginning - from A3XX to A380 (1996-2001)

Strands

By the mid-1990s, the fibre-metal laminate project was approaching the end of its second decade and although a lot of data, models and experience had been obtained, there was still no general acceptance of the material in the aircraft industry. Glare remained one of the very promising materials for the future, a nice status, but one that could not last forever. Certainly no progress could be expected in the U.S., where Boeing had shut the door. In Europe the basis of acceptance and support also remained small, as we saw in the previous chapter. There was no large-scale application and no break-through. Business opportunities for the material were uncertain, and the material still required a lot of investment. As a result, the existence of SLC was also insecure. On the other hand, fibre-metal laminates had certainly been a success for the education of engineers in Delft – a fact reflected in the large number of thesis reports shown in the appendix of this book. It offered the students a serious project with many

technical challenges. However, as we saw in the last part of the previous chapter, the efforts of Delft University needed a strong impetus, because other projects also took up the time of the small university staff, Vogelesang, Sinke and myself. The work of Schijve on fatigue and of Vogelesang on Glare had put the lab on the global map, although the impact of the lab in Delft, measured in the output of journal articles, was not spectacular. Nonetheless, due to its practical philosophy Delft had taken on a leading role in the field of aircraft materials.



Student preliminary design of the A3XX.

However, Glare had finally been put to the ultimate test that would prove whether or not the concept was viable, and the fact that it passed with flying colours speeded up the development work considerably. Various strands in the material's development built up in the past now came together: good contacts with the Dutch government led to trust and financial support, good relationships with the higher management of Airbus supported the material in the organisation, and the established working relationships between engineers and specialists in Hamburg, Toulouse and Delft made teamwork and easy exchange of information possible. For Delft, it was a joy to co-operate with Airbus. The jump in acceptance and technological

maturity, which was achieved during the next four years, would be spectacular. A constellation of many positive factors for Glare appeared on the horizon.

First of all a completely new and ambitious aircraft was considered by Airbus, a project which required all the available technological knowledge and capabilities to be stretched to the limits. Aviation had always developed in cycles: periods of growth, followed by periods of recession. However, after the Gulf War recession of 1990-1991, aviation experienced a period of growth, only interrupted by a period of low production rates in 1993-1995. Aircraft manufacturers had to work hard to deliver their aircraft. Had Fokker still been around after 1996, its prospects would certainly have improved. The way in which the world aerospace industry had developed led to only two competitors that built large passenger aircraft remaining by the end of the 1990s: Airbus Industrie in Europe and Boeing in the United States. Airbus Industrie had started out as a consortium of European partners in 1968 and from its inception had to find a way to compete against the US industry to gain a part of the market. Right from the start, Airbus had sought a competitive edge through better technology than its rival, yet introducing new technologies involved taking risks. Boeing, on the other hand, could play it safe and focus primarily on cost reductions while still making it hard for Airbus to penetrate the market.

After a long period in which few new commercial transport types had appeared, new aircraft projects started to be considered and developed, giving new technologies like Glare a chance. Airbus started an ambitious study on the largest passenger aircraft ever built. While under development, this super-jumbo was named the A3XX, being given its final designation, the A380, once it was officially launched. With this aircraft, Airbus finally entered the market segment of very large aircraft that had been the monopoly of Boeing since the end of the sixties. Up until this point, the American company was therefore able to cross-subsidise its own products. Making a lot of money with its 747, Boeing made competing on smaller aircraft more difficult for Airbus. However, Airbus did not want to be a niche player like McDonnell Douglas had been before it was taken over by Boeing in August 1997, and had to respond. Airbus' target was to capture a 50% market share in its competition with Boeing. This was realised in 1999, in which year Airbus sold more aircraft than Boeing for the first time in history. The success of Airbus was amazing.

One of the strands from the previous chapter that had an impact on this was that Thomas Beumler from EADS Hamburg was linked to the work on the Airbus competitor to the Boeing 747. In 1995, at the time when the 'Dolores' reorganisation caused job cuts, engineers worked in their own time on proposals to speed up the decision making process for the A3XX by increasing productivity, therefore preventing having to lay off even more employees. Beumler played an active role in this and was therefore soon assigned to the A3XX when this project started. In this way he became one of the first two stress engineers working on the aircraft's fuselage. This position was also partly due to the fact that he was one of the very few engineers in the world that was acquainted with Glare. Based on his experience, he introduced Glare from the beginning as an option for fuselage skin applications. As well as this, it was Beumler who drafted the first plans for the barrel test that would be performed on a section of the A3XX fuselage, and Glare was included and defended by him. Fortunately, he was teamed with a colleague from the A3XX programme management, Günther Heidenwolf, who took care of the political, organisational and commercial Glare issues inside the Airbus community and between the Dutch and German players. Both Heidenwolf and Beumler convinced the German management, headed by Dr. Schneider, of the viability of using Glare on the A3XX and Dr. Schneider would play an essential role in the material decision process for the aircraft.

Very large aircraft

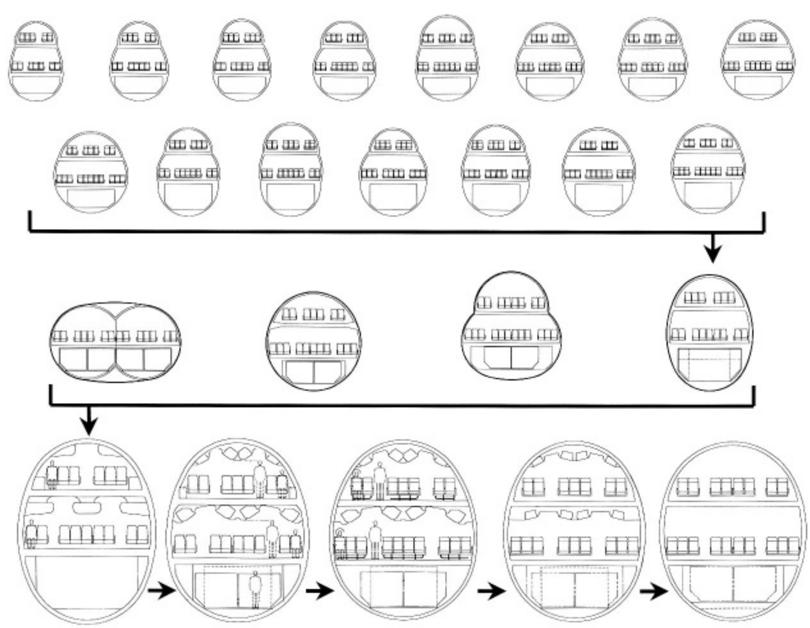
In 1989, Airbus started the first studies on a Very Large Commercial Transport for 550 to 800 passengers. For two reasons, such a large aircraft was a technological challenge. In the first place Airbus faced a commercial challenge: the A3XX would have to compete with the Boeing 747, an aircraft that was initially designed in the 1960s and therefore had a relatively cheap price tag. The second challenge lay in technology: In theory, when the size of an aircraft is expanded by a certain factor, its volume (and therefore its weight) increases with the factor to the third power. But the area of the wing, the lifting surface, increases only with the square of the factor. In other words: if one doubles the size of an aircraft, it will have eight times the weight but needs only four times the wing area in order to balance the weight to provide the lift necessary to keep the aircraft in the air. This 'square-cube law' means that the weight problems of a large aircraft are

enormous. By manipulating the aircraft's configuration, clever designers can successfully fight this law, but new technologies and therefore also new materials play a key role for very large aircraft. However, the first studies showed that the development costs of the Very Large Commercial Transport would be very high. It seemed likely that the market might therefore be too small to be worth competing for.

Therefore, in 1993 the two rivals, Boeing and the Airbus partners Aérospatiale, British Aerospace, CASA and DASA signed a Memorandum of Understanding agreeing to perform a joint study. The second phase of this study was completed in July 1995. Although technically feasible, the market studies did not lead to a common view. According to the Airbus partners, 1200 very large aircraft would be needed over the next 20 years, while Boeing estimated a much smaller market and considered that the Very Large Commercial Transport was not a viable aircraft at that moment. These divergent views were the reason for the 'divorce' between the U.S. and Europe.

However, Airbus still had to close the gap with Boeing. In order to leapfrog Boeing, an aircraft had to be designed that would be bigger than the 747 but that could be shortened to the size of a 747. Several possible concepts had been considered, including combining two A340 fuselages into one big aircraft with the fuselages next to each other, forming a sort of gigantic aerial catamaran. In the period 1994-1996 a dedicated 'Core team A3XX' led by Jean-Jacques Huber further studied the possibilities of the A3XX. For example, early in 1996 a study of the ideal shape of the cross-section of the aircraft fuselage led to 30 possible geometries. Bernd Trahmer, Hans Fischer and Ali Cabac must be regarded as the fathers of the fuselage definition. In the summer of 1996, Airbus Industrie briefed fourteen airlines on the specification of a very large aircraft, designated as A3XX. The company had created a Large Aircraft Division in Toulouse, headed by Jürgen Thomas. At the end of 1997, a preliminary design was selected that was already very similar to the current configuration, and the predevelopment phase started. Airbus had chosen a double-deck fuselage configuration over the full length of the aircraft. Boeing's 747 also has an upper deck, but only for approximately a quarter of its length. The main target was to reduce the direct operating costs of the A3XX by 15 to 20% compared to its rival, the Boeing 747 jumbo jet. Part of the answer to this challenge lay in economies of scale, part in a significant reduction of fuel consumption. Right from the start, Boeing spread doubts about the viability

of the A3XX, predicting a much smaller market for aircraft in the category of the A3XX than Airbus had. This was in part caused by the fact that Boeing expected a change in the structure of air transportation: fragmentation of traffic flows. In the previous decade, air transport had developed hub-and-spoke systems in which small aircraft first transported passengers along a ‘spoke’ to a central airport, the ‘hub’, and combining traffic flows there to be able to use larger aircraft for the final destination. While offering substantial cost savings to the airlines, and enabling a reduction of air fares, this form of operating was less convenient for the passenger because it involved at least one transfer in a typical journey. Boeing therefore expected that route fragmentation would occur with more direct point-to-point flights. Airbus, by contrast, was convinced that abandoning the hub-and-spoke system would increase ticket prices, which would be unacceptable for most customers. It proposed the A3XX as the next logical step in aircraft development. In the 1970s, the Boeing 747 had doubled the productivity of aircraft, but after the initial rapid growth of air transport that it caused further developments in economies of scale had ceased.



Fuselage cross-sections studied for the A3XX.

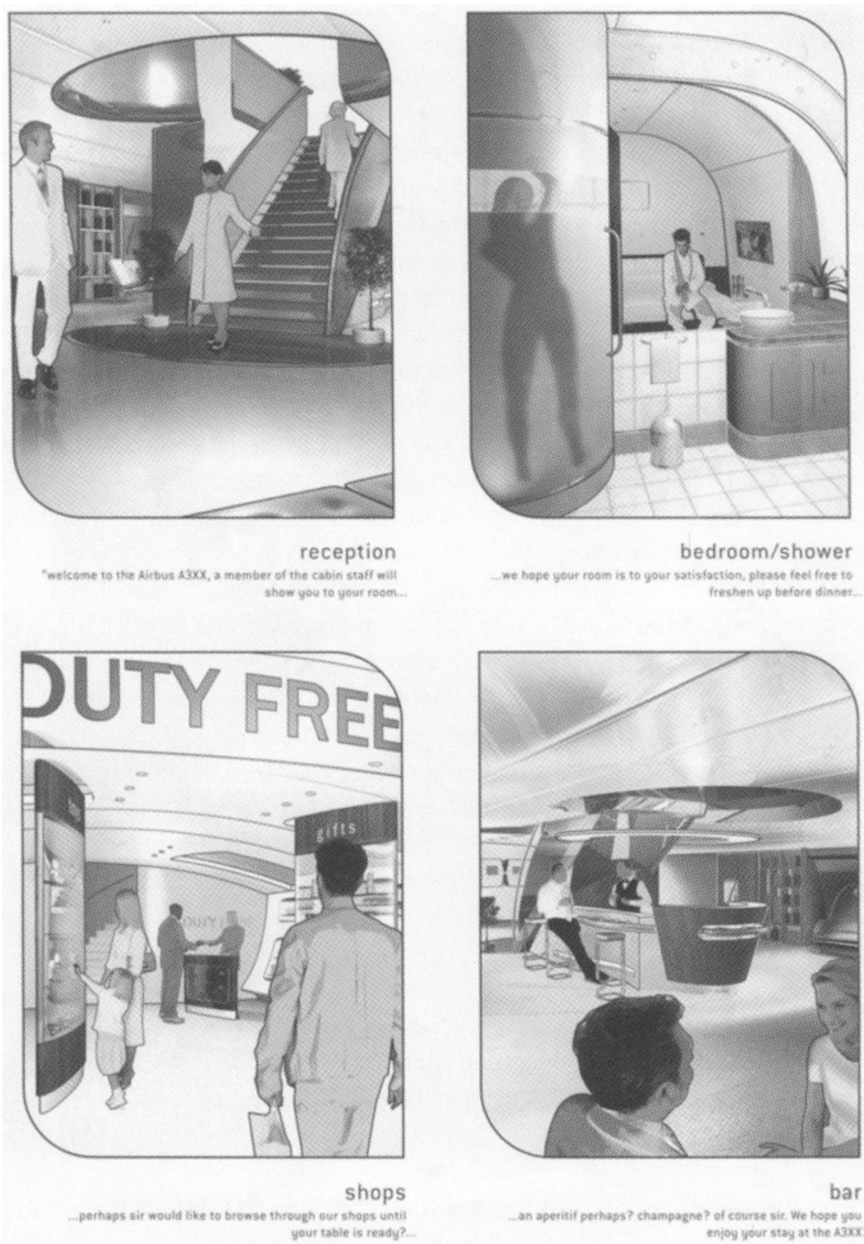
The change to modern aircraft in the 1930s, then to jet aircraft in the 1960s and to wide-body aircraft like the 747 in the 1970s had caused revolutionary changes in the scale of aviation. Airbus expected the A3XX would pick up this line of improvement in productivity, facilitating the expected growth in air transport of five percent per year that would double the traffic in fifteen years. In the face of this development, airports were expecting serious congestion problems. Using larger aircraft would mean that airports could be used more efficiently with less take-off and landing 'slots'. Airbus predicted a need for more than 1300 aircraft in the A3XX category in a total market of 14,000 new aircraft. Although the share of the very large aircraft would be only ten percent, it represented a quarter of the value of the potential business. Therefore this market could not be left to Boeing. Airbus expected the main demand for such a machine to be in the Asia-Pacific region.

The designs released by Airbus showed that passengers in the A3XX would be accommodated on two decks that would be connected by a large staircase. The A3XX is being promoted as a spacious aircraft that could even be fitted with a bar, a fitness centre and sleeping cabins with showers. In an advertisement it is characterised as a flying hotel and in a video clip as a kind of love boat. The sheer size of the A3XX stimulates the imagination. The A3XX was designed as a family of aircraft from the start, with shorter and longer versions and also a freighter aircraft. The freighter version appeared to be very attractive for transport companies like Fedex because of the rapid growth of parcel transport and mainly because the long range of the A3XX offered the possibility of direct flights and therefore the introduction of new routing systems that could save precious time. The introduction of the freighter version of the A3XX therefore soon got a high priority, which is unusual for a new aircraft. The first version of the A3XX, the A3XX-100 would have an empty weight of 250 tons, a maximum take-off weight of 560 tons (compared to the 747-400s maximum of 397 tons) and can carry 550 passengers. This giant would also have engines that are quieter and produce fewer emissions than today's aircraft. The growing environmental concerns for the growth of aviation in the media were certainly treated seriously. The concept of the A3XX is such that no airport modifications will be needed. The new giant will not require the large investments in infrastructure that were necessary with the introduction of jet aircraft in the 1960s. As a result of this decision, the dimensions of the aircraft had to stay within a box of 80 by 80 metres. The A3XX-100 will be 71 metres long and

will have a wingspan of 79 metres. These boundary conditions impose even more stringent technological demands since a smaller wingspan tends to jeopardise efficiency as it has a negative effect on the lift-to-drag ratio of the wing. The development costs of the A3XX were estimated in 1996 to be in the order of $8-10 billion.

From the start, Boeing had plans to offer a stretched version of its 747, the 747-X, as a competitor. It would have the advantage of lower development costs and an earlier entry into service than the A3XX. However, uncertain about the course of developments, Boeing stopped and restarted the stretched 747 project several times. In discussions with airlines, competition was tough and the stretched 747 never found a customer. On the other hand, the A3XX did not have plain sailing either. The aircraft was originally planned for an entry into service in 2003, but in 1998 this was postponed to 2004, in 1999 to 2005, and in 2000 to 2006. The reason given was that Airbus had not yet achieved the targeted 15 to 20 percent reduction

Airbus advertisement.



A380 stimulates imagination.

in operating costs relative to the 747. The economic crisis in Asia, which was an important market for the A3XX, probably also had a lot to do with this. A further problem is that Airbus was simultaneously working on the development of another aircraft, the A340-500/600, which absorbed a lot of its engineering capacity. To complicate things even more, Airbus also started the development of the A318, a 100-seater, and the European partners were also working on the A400M, a military transport aircraft. Airbus engineers were indeed facing stressful times. In fact this delay was essential to the potential for applying Glare, since it created the time needed to close the technology gaps and to strengthen the necessary support throughout the company.

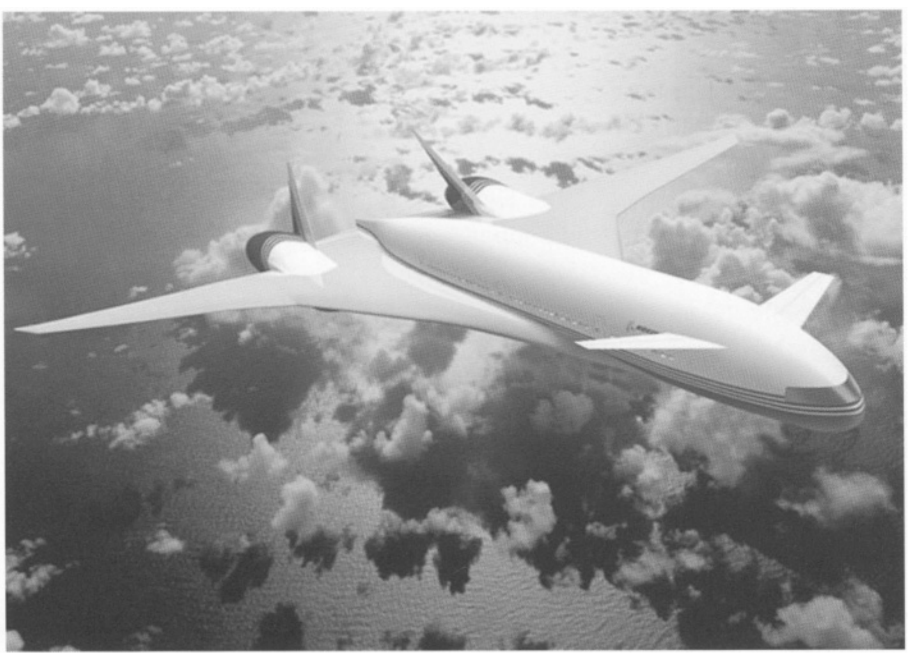
Because no customers were found for the stretched 747, this project was finally cancelled in March 2001. At the same time, Boeing introduced its design for the 'Sonic Cruiser' – an aircraft for 250-300 passengers which has to be able to cruise close to the speed of sound: at Mach 0.98. This is 15-20% faster than the 747, which is the fastest subsonic transport in service today. Like size, speed has not lost its appeal in aviation. Boeing had been considering faster supersonic aircraft for a long time, re-visiting the traditional controversy in aviation of speed against size. The Sonic Cruiser is a manifestation of Boeing's belief in fragmentation. Many observers feel that this idea was proposed to divert attention away from Airbus' very large aircraft – and from Boeing's failure to launch the stretched 747. Others think that the increased speed can in many cases lead to a higher number of round trips for each aircraft in a day and therefore to higher productivity. Boeing estimates the potential market to be 5,000 aircraft. Entry into service may be between 2006 and 2008, depending on the new technologies that the airlines require. The magazine *Flight International* says about the Sonic Cruiser:

> "Material choices range from current technology, 777-style, composites to the widespread adoption of non-metallics and advance materials. This includes high-performance composites such as Glare..."[1]

The difference between the A3XX and the Sonic Cruiser reflected the difference in opinion that grew in this period between Europe and the U.S.,

[1] *Flight International,* 12-18 June 2001, p. 103.

not only regarding the development of air transport, but also the seriousness of environmental issues. The fuel burned by the Sonic Cruiser during sustained high-speed flight is about 20% higher than conventional aircraft. It was probably more than a slip of the tongue when Boeing's vice chairman Harry Stonecipher defended the Sonic Cruiser with the remarks "plenty of fuel still around" and the "environmental bandwagon". European environment commissioner Marget Wallstrom responded furiously and sent Stonecipher a letter in which she asks: "...whether a one-hour time saving on a transatlantic flight is worth a significant increase in carbon dioxide emissions contributing to climate change. In my view, this environmental price is simply not worth paying."[1]



Boeing's design for the Sonic Cruiser.

[1] *Flight International,* 3-9 July, 2001, p.6.

Media interest

Almost from the start of the A3XX project, Glare was mentioned by Airbus in the press and in conference presentations as a serious candidate for fuselage material. The area under consideration had previously been restricted to the upper half of the fuselage skin since Airbus expected the biggest advantage for Glare in this area, where damage tolerance is usually the design driver. The upper part of the fuselage is usually dominated by fatigue initiation, crack growth and residual strength while for the lower part the static loads in compression are usually critical for the design. Glare is especially outstanding in fatigue, while the buckling stress under compression may be lower than that of aluminium alloys. A weight saving of 1.5 tons due to the use of Glare in this upper part was expected at that time. The complex double curved cockpit and tail sections were considered to be too complicated to be manufactured from Glare. This restriction also had to do with the fact that also other new technologies in which Airbus partners had invested heavily had to find a location in the fuselage.

The lower half of the fuselage would be constructed from aluminium alloys that would be laser welded, a new technology developed by the German and French partners of EADS. Also, new aluminium alloys had to find their way in. It made the support for Glare all the more remarkable as the development of the A3XX presented an extremely big risk for the company and the large-scale introduction of a new material in this way had never been done before. The plans for Glare also meant that Delft was soon in the spotlight, because Airbus again and again linked Glare to Delft. It was raining articles on the combination of the A3XX, Glare and Delft, being featured, for example, on the front page of *The Wall Street Journal* European edition of September 7, 1998. *Flight International* also mentioned Glare frequently, for example in the issue of June 11-17, 1997, where it said:

> "In terms of technology, however, there are several features which will make the aircraft significantly different from its predecessors. Perhaps the most potentially exciting is the possible extensive use of a new aluminium alloy/glass fibre reinforced plastic composite material (called Glare) for the entire top half of the fuselage."

Other media also showed interest. On the 5th of April 1999 *Discovery Channel* made a television documentary on Glare in the Delft lab and at Fokker Aerostructures. Being a university, it was part of Delft's mission to give information, resulting in a number of presentations on this development at international conferences. Articles on Glare in scientific and trade journals also drew attention. On the 14th of April 2000 De Vries and I even travelled to London to pick up the prize for the best article in 1999 in *Aircraft Engineering and Aerospace Technology,* although this reflected primarily, perhaps, the growing interest in the work that was carried out on Glare at that time, rather than our writing skills.

Award for excellence with, from right to left, Tjerk de Vries, the director of the British Library and Ad Vlot.

The possible application of Glare and the possible Dutch involvement in the A3XX brought Jürgen Thomas, the head of the Airbus Large Aircraft Division, to Delft. On the 15th of November 1997 he gave the Simon Stevin Lecture on the occasion of the 155th anniversary of the university. He stressed the reputation of Delft and the fact that, despite the loss of Fokker, the Netherlands continued to have a substantial involvement in the aviation industry. Thomas stated that to cover the enormous development costs,

Airbus Industrie was looking for new risk-sharing partners and that he would like to see a Dutch Airbus which would unite all the Dutch efforts in the aviation industry: Fokker Aerostructures, NLR, SLI, and TU Delft. Indeed, partners outside the consortium participated for a total of 20% in the project. Apart from Fokker Aérostructures, Alenia (Italy), Belairbus (Belgium), Saab (Sweden) and Finnavitec (Finland) also held interests in the project. The aim was to raise third party participation to 40%.

Thomas was not yet able to announce the location where the new aircraft would be assembled, but the strong competition between Hamburg and Toulouse for the prestigious final assembly line was later won by the French, Aérospatiale. The transport of the gigantic parts of the A3XX to Toulouse remained a big issue.

In July 2000, the Large Aircraft Division finally received authorisation to offer the A3XX to customers. The launching customer was the Dubai based airline, Emirates, which ordered five aircraft, followed by an order from Singapore Airlines of ten aircraft. Already sales of the A3XX looked promising. The launch threshold was set at fifty orders and at the end of 2000 the count stood at forty-four, plus thirty-six options. In the period up to March 2001 this figure increased to sixty-six firm orders. In the meantime, the A3XX became the A380 at its official launch in December 2000.

Hinrichsen

At the Airbus Large Aircraft Division in Toulouse the director of structures engineering was Jens Hinrichsen. Hinrichsen was seconded to this position by DASA in Hamburg on the 1st of July 1996. He knew Jan Willem Gunnink very well from the time that Hinrichsen worked in a German-Chinese project known as MPC75. This was a programme (also headed by Jürgen Thomas) for a 100-seater aircraft, which started in 1988, but was never realised. The duo of Thomas and Hinrichsen became major allies, promoting Glare and giving it the chance to finally prove itself. Jens Hinrichsen concentrated his efforts on the many new technologies in the structure of the A3XX, including welded aluminium structures, cast doors, thermoplastic composites, carbon composites and, especially, Glare. Of these other promising new technologies, thermoplastic composites had also originated in Delft. It was developed by a colleague of Vogelesang in the office next to his: Willem van Dreumel of the composites group. Van

Dreumel, however, left the university to work for Ten Cate, where he was able to produce the material for Airbus in large volumes.

Jens Hinrichsen was a strong supporter of Glare. A very energetic and keen engineer, he started his career as a carpenter – another craftsman, part of the ‘red thread’ throughout this book that started with the Wright brothers. Being energetic, Hinrichsen left his school in Germany at 16 years old to become a carpenter according to the wish of his grandfather – also a carpenter – who promised him his toolkit if he would do so. For three years, Hinrichsen was educated as a carpenter and learned to make roofs and staircases. Much later, working for Airbus, this experience stood him in good stead, giving him an acute awareness of the importance of practical experience in manufacturing. At the age of 19, he went back to school, attending the engineering school of Lübeck where he studied civil engineering. He graduated and worked for three years as a stress engineer in civil engineering consultancies, checking the calculations for buildings for local government departments. In 1971, he moved to Hannover to continue his studies at the university and improve his theoretical background. He was very interested in a difficult subject: mechanics. Hinrichsen selected courses in fluid mechanics, acoustics and vibrations. His thesis was on failure due to aeroelastic problems, i.e. the combination of wind loads and induced vibrations such as those that caused the famous collapse of the Tacoma Bridge in Seattle. Aeroelasticity became his speciality and he went to work in this field for VFW-Fokker in Bremen. Starting with a wind tunnel programme for the Airbus A310, he was involved in this field for the other Airbus aircraft during the next ten years. During this period, he also became acquainted with stress and fracture problems after meeting Lüder Schwarmann. Schwarmann showed him two brochures on Arall and taught him to appreciate the material from a fracture mechanics standpoint. During this time, Schwarmann became involved in the barrel test with Thomas Beumler and Gunnink, as was described in the previous chapter.

Hinrichsen first met Gunnink during the MPC75 programme. Hinrichsen was assistant to the vice-president of industrial engineering, dealing with manufacturing, material, fatigue and stress calculations for the aircraft. Early in the programme, around 1992, Rob van Oost of SLC performed a study on the application of ALCOA’s new aluminium alloys in the wing of this new aircraft. The work on aluminium alloys was done by SLC to support ALCOA at a time that ALCOA was losing interest in the laminates. As was mentioned in Chapter 3, ALCOA lacked the design capabilities for

this kind of work. Van Oost found a three to five percent weight reduction for the new alloys, which was rather disappointing. Hinrichsen met Gunnink during this work and Gunnink told him that if he really wanted significant weight reduction he had to think about a different material: Glare. He advised Hinrichsen to talk to Professor Schwarmann and Thomas Beumler. In the penthouse office in Hamburg, with its panoramic view over the river Elbe, a first meeting on the possibilities of Glare was held with Bill Evancho, the president of SLC, and Gunnink. Glare was included in the study, but from his aeroelastic background Hinrichsen judged that because of its low torsional stiffness, it would not be suitable for the wing of this aircraft. The material would be better suited for the fuselage.

Like Beumler, Hinrichsen was somebody with the energetic drive necessary to make a new technology gain acceptance within a big company like Airbus, despite its hurdles and inherent inertia. For a long time the main obstacle was the price of the material, which was twelve times higher per kilogram. Although Jürgen Thomas became head of development of DASA in 1993, and in this position was able to protect Glare from being scrapped for financial reasons, it was Hinrichsen who was the main drive behind finding a solution to the cost problem. However, for reasons of business

Jens Henrichsen.

Memo Daimler-Benz Aerospace Airbus

Daimler-Benz Aerospace Airbus, Hamburg 20th June, 1996

From: J. Hinrichsen, EZ
Tel.: (40) 7437 - 4932, FAX: (40) 7437 - 4755

Reference: Telephone conversation Hr. Thomas/Hr. Hinrichsen on 18th June 1996

Subject: **Glare application for fuselage shells**

To: H. J. Thomas, AI/L
M. J.-J. Hubert, AI/LE
M. H. Ostendorf, AI/LI
H. Oelwein, DA/WM

For Information: H. H. Schnieder, DA/EZB
H. T. Beumler, DA/EMF
H. H. Oelkers, DA/EZ
H. R. Genoux, DA/TC1 (Bremen)
Dr. Schwarmann, DA/EMF (Bremen)
H. Bierfischer DA/EZC

The most recent letter send from SLC to AI/E gives good reasons to review the status of assessment of GLARE application for fuselage shells of A3XX. As a matter of fact, the material price situation we were confronted with (10 times the price of standard aluminium alloy 2024T3) has blocked for long a comprehensive investigation in terms of structural design/damage tolerance/manufacturing aspects. As natural consequence, the cost/benefit pilot study "GLARE" (which I have initiated in November 1994 in the frame of the 3E Programme) has failed up to date to deliver a complete picture - despite all the efforts and trials of the cost group members to collect the necessary information from the various disciplines.

These days I have resigned from chairmanship of 3E's Technical Management Group. However, because of my personnel engagement in this topic, I would like to give my view as follows.

1. Technical issues

The key issue related to GLARE is it's contribution to a "damage tolerant structural design": The crack growth rate is much less compared to standard aluminium alloys. In other words, the number of flight cycles between occurrence of damage and fatal failure is largely increased. Consequently safety as well as inspection intervals are positively affected and it might be regarded as a big step towards a so-called "care-free structure".

The specific feature is simply due to the glas fibres which run across the trace of the crack: the crack comes to a hold or the crack growth is largely decreased. GLARE helps to save weight in the shells of a fuselage in all such areas, were residual strength and/or crack growth is the design driver. From analytical investigations on A340 we know, that this is the case for about 60% of the cylindrical part of the fuselage shells. Savings of manufacturing cost can be expected, because longitudinal lap joints

Memo of Jens Hinrichsen to Jürgen Thomas.

MEMO Daimler-Benz Aerospace Airbus

EZ/108.96-Hin, 20th June 1996

can be simplified (as verified by DA's barrel test after more than 100000 flight cycles) an estimate of weight saving is based on a comparison of design stress levels for various materials. With this we have to distinguish between circumferencial and longitudinal (flight-) direction. Thomas Beumler from DA's "fatigue department" has worked out the figures in Table 1, which allow to judge different skin materials for A3XX on the basis of 530mm frame pitch. Aiming at a design which covers the "two-bay crack criteria" – as realised on B777 with 530 mm frame pitch – the stress allowables in circumferential direction are relevant, except for C188.

skin materials	design stress levels, circumferencial, [MPa]	design criteria	design stress level, longitudinal, [MPa]	design criteria
2024 T3	67	residual strength	89	crack growth
GLARE 4	85	residual strength	>110	crack growth
GARE 3	78	residual strength	>120	crack growth
C188 (B777)	76	crack growth	89	crack growth
6013	78	residual strength	85	crack growth

Table 1. Comparison of design stress levels for various materials for A3XX application

2. Status of Cost/benefit pilot study

The work of the cost group of 3E's Technology Assessment Group (TAG) is based on P500-200 configuration.

2.1 Basic assumptions/limitations

- The area for GLARE application is limited to the upper shell in the cylindrical fuselage part.
- NRC are not covered.
- Both, added value for the customer in terms of less maintenance cost as well as effects from increased flame resistance are not quantified.

2.2 Results

- About 700 kg primary weight saving; 1200 kg including snowball effects.
- Cost increase: about .81M$ per A/C.

The increase in cost covers material cost (prices as given before recent SLC information) of as well as an increase of manufacturing cost, the later representing an average value of 3E partner's estimates. The scatter band is not given. (The DA figure is plus .2M$ per A/C, which gives a clue of on the scatter).

Memo of Jens Hinrichsen to Jürgen Thomas (continued).

MEMO Daimler-Benz Aerospace Airbus

EZ/108.96-Hin, 20th June 1996

The impact of material price reduction – as a result of recent SLC information – needs to be agreed by the cost group.

3. Recommendation for "The way forward"

Information from TAG member Hans Schnieder, DA/EZB, on the status of GLARE assessment give strong indications that we are close to the point, were we can reach the target to neutralise the effects from higher material cost, and this in combination with added value given to the customers. This takes into account the most recent SLC's price reduction. It must be kept in mind, that the prices are linked to specific orders of annual volumes, which we do not meet with GLARE application limited to the upper shells of the cylindrical fuselage sections. However, now it becomes an industrial issue and we would weaken our position, if we would allow for further information drain towards SLC, as I experienced in the past with cost figures. Also this aspect is addressed by the following recommendations:

, Transfer of all issues related to prices to purchase departments.

, Install an integrated team for a comprehensive evaluation of all technical matters concerning GLARE:

- Risk assessment (incl. proposal for in-service trial),
- Review of existing investigations and identification of gaps for technology,
- investigation of application to lower fuselage shells,
- design of critical areas, specific to A3XX,
- material qualification,
- quality assurance aspects,
- certification,
- manufacturing processes & cost,
- supplier involvement, e.g. delivery of components (with doublers, etc.).

For sure, the list above needs to be completed, but gives an indication for the needs and the required effort to be spent befor a decision can be taken on proper ground.

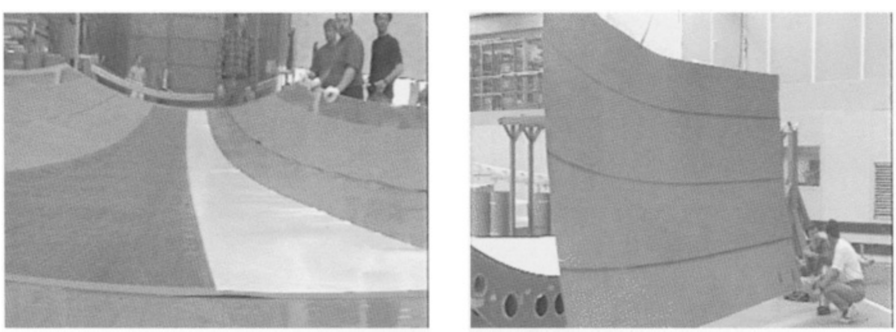
Best Regards

Jens Hinrichsen

Memo of Jens Hinrichsen to Jürgen Thomas (continued).

policy ALCOA set a price for Glare that was twelve times higher per kilogram than that of its main product, aluminium. Later this was reduced to a factor of eight. Airbus was only willing to apply Glare if the Glare structure could be produced for about the same cost as aluminium structures.

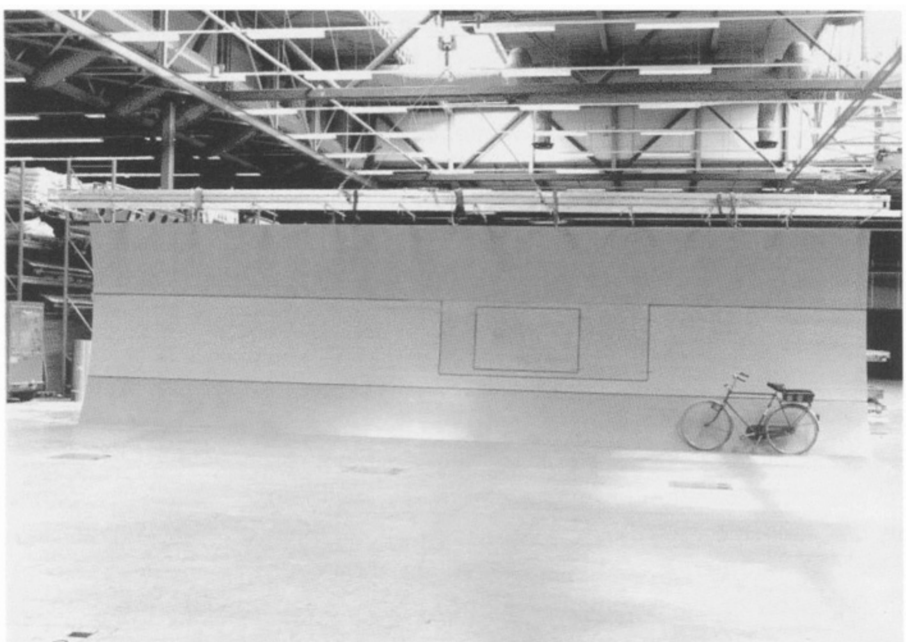
Around 1994, it was proposed that a fuselage section be produced by roll-forming a flat sheet and then bonding the necessary reinforcements on it. At this time, Hinrichsen became responsible for controlling technology development at DASA and he managed the Technology Programme (3E) aiming towards preparation for the A3XX. A small part of the 3E programme was the experimental installation of Glare floors in Garuda aircraft in 1995/96, which was possible, as we have seen, because of the Indonesian PhD-student Soerjanto. The programme also included Glare fuselage shells. This was the second project in which Gunnink worked with Hinrichsen and had the opportunity to establish a good personal friendship and to exchange the ‘Glare-virus’.



Production of a large curved Glare panel at Fokker Aerostructures.

In 1995, Hinrichsen initiated a cost study as a pilot project for the technical evaluation of the 3E programme. A cost study was done for Glare for the A3XX in which Hinrichsen had become involved in the previous year. Although the cost study showed awful results for Glare, this did not shake Hinrichsen’s belief in the material. The study showed that Glare could not be competitive when it was applied as sheet material. However, he also found that the price of Glare was artificially high due to political reasons. Based on his experience with carbon composites, Hinrichsen proposed a similar manufacturing process for Glare using a curved mould to produce complete panels instead of sheet material. Late in 1995, discussions started with Gunnink’s group who also came up with the idea of producing Glare not as a

semi-finished flat sheet but in a curved mould like composites – producing products instead of material. Roebroeks managed to fully develop this concept including the splice technology. The Glare technology now became really attractive. At that moment ALCOA walked away from the project.



Large curved panel made from Glare.

Heidenwolf paper

After Hinrichsen's move to Toulouse in July 1996, the contact between Hinrichsen and Gunnink became more frequent, which was essential for the application of Glare on the A3XX. Just before he left to become director of structures of the A3XX, Hinrichsen was asked by Jürgen Thomas what the status of Glare was at that moment. His reply in a memo is reproduced elsewhere in this chapter. Hinrichsen clearly described the great potential of Glare relative to its competitors because it could produce weight

reductions in the order of some 1,200 kilos: 700 kg in direct savings, plus another 500 kg in ‘snowball effects’ (a lower structural weight means smaller undercarriage, smaller engines, and so on). However, the gaps between the present status of Glare and its industrial application were still very large. Hinrichsen indicated the way forward: further price reduction, and an integrated team for a comprehensive evaluation of all technical matters concerning Glare. These two issues were the cornerstones of the further development of Glare. With the support of Thomas and Hinrichsen it was possible to gain the support of Airbus’ top management for Glare. It seemed there was light at the end of the tunnel. Instead of pushing Glare from the level of specialists and engineers to the top management, the gap was closed by someone who rose within the organisation to the position of director of structures for the A3XX.

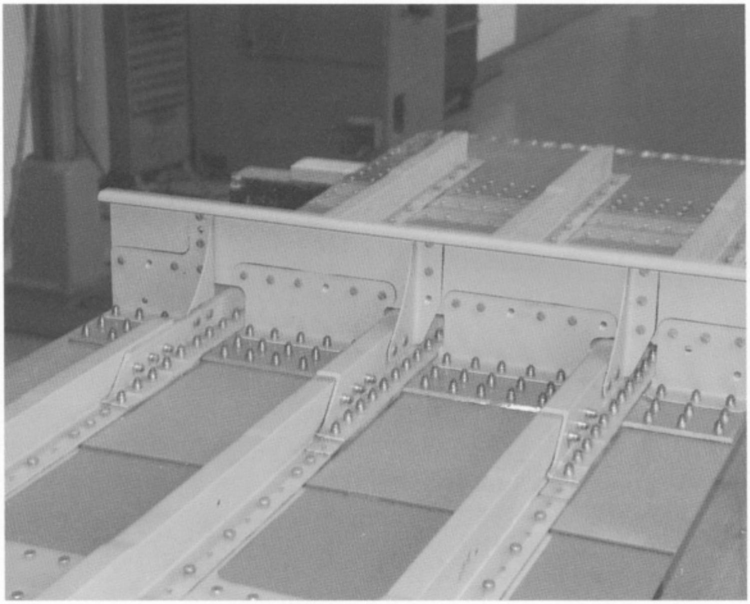
Hinrichsen tackled the need for a comprehensive effort on all technical aspects head-on. Just before Christmas 1996, a meeting between the Large Aircraft Division, DASA, Aérospatiale and Structural Laminates bv was held to discuss what was still necessary for Glare in order for it to be applied in aircraft. Twenty years of work on fibre-metal laminates in Delft had accumulated a lot of experience and data, but there was no comprehensive system for data and reports that covered all relevant aspects of the material in a format that could be used by Airbus. Also, not all relevant aspects were covered, for example industrialisation. Many ‘white spots’ were still present in the technology. Through the years, numerous different fibres and adhesives from different suppliers had been used, which made it problematical to compare data. A lot had to be repeated or incorporated in a structured manner. Time now became essential to meet the time schedule of the A3XX.

Also present at this three-day meeting was Günther Heidenwolf of EADS in Hamburg. Together with Beumler he had prepared a list of items that had to be covered. On the basis of the different sessions of the meeting, he prepared a document in which he carefully defined, in a highly structured way in terms of technical content and required man-hours, the more than one hundred projects necessary to make Glare mature. This document was excellent, an example of ‘Deutsche Gründlichkeit’ in a very positive sense. In the last phase of the development of Glare, the ‘Heidenwolf paper’ pointed the way ahead. The document was, however, never officially signed and released because the situation around SLC was unclear and therefore there was no reliable industrial partner to produce the material. Heidenwolf was

appointed by the A3XX-management and was the first in the Airbus-organisation who could spend a significant part of his time on Glare. He remained heavily involved in the management of the Glare project. Together with Beumler, he had to answer and neutralise all rumours and doubts that arose within EADS during the pre-development phase of the A3XX when more and more specialists became involved and the fight between the different camps intensified.

Students

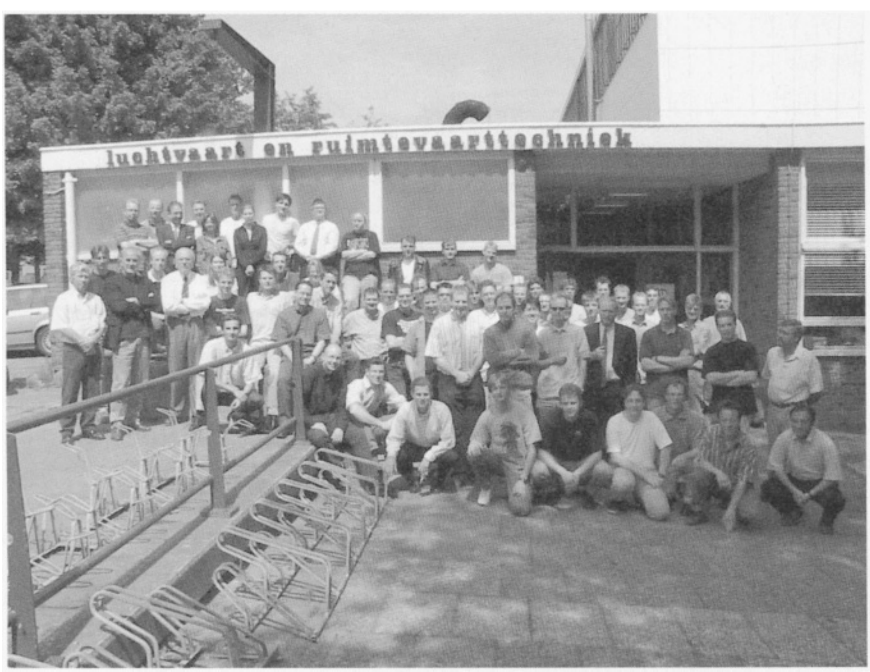
The impulse that Delft, including both the university staff and the staff of Structural Laminates-bv, had already given by defining projects for students on the A3XX was very successful, although it created an extremely busy period for the very small Delft group in guiding all the students. A lot of students found it attractive and motivating to work on this new, largest aircraft ever built. These were no routine assignments, but the exploration of the boundaries of technical possibilities never touched by anyone before. Explorations like this were well suited to a university group, which was a benefit for Structural Laminates. A number of students began their thesis work at that time and meetings were held on a regular basis to make sure that there was enough interaction. Erik Kroon studied impact behaviour. Martijn Vervaet studied the longitudinal joints, which have a different behaviour for the large thicknesses of the A3XX. Pieter Boersma did a preliminary design leading to critical load cases and the initial required thicknesses of the fuselage skin. Stephan Vissers looked at the circumferential joints. Sjoerd Verhoef and Martin van Onna studied the cut-outs, i.e. doors and windows. Giel van der Kevie did work on the material's fire resistance, which was absolutely essential for the safety of the aircraft. Peter Hooijmeijer examined the splices. Jan Soede investigated manufacturing techniques. Willem Vesters worked in Hamburg on residual strength. Occo Jan Bosker and Lucas de Kraker did blunt notch strength. René Alderliesten did fatigue. Henk Pandee started design work. Walter de Ruyter also tackled the splices. Alexander de Haan worked on damage tolerance. Geoff Morris worked on joints. Peter Broest studied production aspects. Bob Borgonje looked at durability. Many other students also worked under the guidance of Structural Laminates and the university staff on different aspects of Glare.



Glare circumferential joint test panel.

Residual strength test panel with a crack simulated by a saw cut, tested by student Willem Vesters.

Staff and students (around 1980).



Staff and students (summer 2001).

The work of the students at Delft served as a starting point and as a reference for the further development of Glare necessary for large-scale application according to the Heidenwolf paper. This paper was expanded by the Structural Laminates staff into a detailed project plan. The students collected the relevant information from the work that was already available and extended their findings towards the A3XX. Also very important was that many of the students caught the 'Glare virus' and therefore were willing to continue to work in Delft after their graduation on temporary contracts, to supplement the university staff. In this way, a dedicated team could be created with the required knowledge in all the different fields covered by the Heidenwolf paper. This was a kind of miracle, since in this period of economic growth there was a tremendous shortage of skilled labour in the Netherlands. Without the success of the student projects, it would have been impossible to carry out the necessary research to establish the technological readiness of Glare, as laid down in the Heidenwolf paper.

Krook

This work on the technology of Glare was possible because of the extensive financial support of the Dutch Ministry for Economic Affairs through the NIVR. The way to this support was paved by Daan Krook, who was aviation advisor to the Ministry. He played a pivotal role at this stage of the Glare development because of his many contacts in the aviation industry. Krook had been commercial director of Airbus Industrie from 1975 to 1979, one of the company's senior CEOs. Airbus had been fighting for its existence since the introduction of the A300 passenger jet in the early 1970s. Until 1975, when Krook arrived, only 22 of the heavily subsidised aircraft had been sold and the distance between Airbus and the American aircraft industry seemed unbridgeable. Krook made the difference. When he left in 1979, the 220th aircraft had been sold. This success in the important early days of the consortium had created a lot of goodwill that remained with him in later years. Krook returned to the Netherlands in 1979 to become a member of the board of Fokker. In 1981/82 he read in a newspaper about Arall, then in the hands of AKZO for further development and marketing. In this article it was mentioned that the future of Arall at AKZO was uncertain. Krook contacted the chairman of AKZO's board, Loudon, with a plan to keep the material and its technology in the Netherlands, which was accepted. When he was fired from Fokker in 1987, Krook took on several appointments

as consultant, and also became an advisor of the board of AKZO. In this role, Krook became responsible for the aerospace sector. He enquired about Arall and was told that Glare had entered the scene in the meantime, a material that worried AKZO because it did not contain any of the ingredients that AKZO produced. Krook was able to prevent AKZO from stepping out of the fibre-metal laminate business. It was Krook who contacted Fokker's board member responsible for technology, Van Duinen, to keep Glare in the Netherlands. Krook promoted Glare for good reasons. He knew fatigue problems very well because he had started his career in the aviation industry at Fokker in 1958. Those were the days when fatigue was a crucial issue, as we saw in the first chapter. In that period the fatigue tests on F-27 wing panels were running, after which Fokker decided to modify the wing. Fairchild refused to carry out the modifications, which led to the F-27 accident over Alaska. This had taught Krook important lessons. As a salesman at Fokker he had spent a lot of time with customers explaining the advantages of bonding of aircraft structures. He also knew of the conservatism within the aviation industry. Glare fitted perfectly into the Fokker philosophy of creating a high quality aircraft structure.

The outcome of the discussions between AKZO and ALCOA was that AKZO kept 1/3 ownership in the joint venture with ALCOA, as was described in the third chapter. At the same time, Fokker was struggling to develop the Fokker 50 and Fokker 100, aircraft that were derivatives of the F-27 and F-28, with the minimum of changes required to make them up-to-date. Glare was a bridge too far for these aircraft. For AKZO, Krook supported Glare wherever he could, using his network of contacts in the aviation world. He pressed ALCOA to support the material but without success, because the company gradually lost interest in laminates. Krook had a better entree at Boeing since one of the executives he knew from his Airbus period was now president/director of Boeing Commercial. Nonetheless, his efforts to get Boeing's top management to support Glare also remained unsuccessful. After reaching retirement age, Krook continued his consultant position for AKZO and began to use his good name within Airbus, where Glare started to become successful as we saw in the previous chapter. Several of Krook's contacts at Airbus Industrie were now holding top positions. For example, the chief of flight-testing was now responsible for the technology of Airbus. In the meantime, Krook was also a consultant at MBB and he knew its boss, who had been head of production in Krook's time at Airbus, very well. Krook

became advisor to the MPC75 project, which was headed by Jürgen Thomas and in which Jens Hinrichsen also played an important role.

From the start, Airbus had been open-minded about new technologies and Krook found fertile ground for his pleas to incorporate Glare. In a period in which the whole aviation industry was looking for cost reductions of 30%, which was why Fokker and Boeing were not willing to consider Glare, Airbus still had an open mind regarding improvements. Severing his ties with AKZO in January 1999, Krook became an advisor to the Ministry of Economic Affairs at a time when it was reconsidering the position of the aircraft industry after the bankruptcy of Fokker. Even before that, however, Krook already had good contacts within the ministry that he had built up over the years. After the loss of Fokker, one of the most important assets of the Netherlands remained materials technology, a sector in which the country was traditionally very strong. In aviation, materials technology is the basis of all other technology and is therefore vital. Krook knew all too well from experience how a sound and promising technology like Glare could become a vulnerable plaything in the hands of the industry when unprotected. We have seen through our story how Arall and Glare only remained alive because a small group of people refused to stop believing in the material and because of the support that Delft University could provide in the form of motivated students. Krook and Gunnink now finally managed to acquire substantial financial means to realise the technological readiness of Glare, which was necessary for large-scale applications such as in the A3XX. On the basis of the plan in the Heidenwolf paper, Gunnink wrote a well-documented request for support from the Ministry of Economic Affairs for further basic material research. In granting this subsidy, the government took a risk, because at that time Airbus had made no commitment to co-operation in a formal agreement. All was a matter of trust and belief.

Krook also discussed strategies with Hinrichsen on how to proceed with Glare in the A3XX project. One of the guiding principles for Krook was that Glare could be the entrance ticket for the Netherlands to future Airbus projects. Gunnink, Krook and Hinrichsen used their dinners in Le Cantou in Toulouse to discuss the problems and to become friends. Krook was well-known within the Airbus community and Hinrichsen relied on his advice. Hinrichsen used the Dutch governmental support to strengthen the political position of Glare. After all, Glare might collapse at any time because of key people in Airbus who did not support it. The link with the government was therefore important. Twice, Dutch government officials visited the Large

Aircraft Division and this made the Glare work very official. Van der Harst, one of the officials, played an important role within the Ministry of Economic Affairs in supporting Glare.

GTO

The Ministry for Economic Affairs had allocated 76 million Dutch guilders (34 million Euros) for the Glare project; 31 million (14 million Euros) for basic Glare technology development (referred to as GTO, *Glare Technologie Ontwikkeling*) and 45 million (20 million Euros) for a barrel test on a fuselage section of the type that would be used for a very large aircraft (a Megaliner) like the A3XX, to verify the design principles for such aircraft. This barrel test was considered extra important because of the many new features of a Megaliner, including the unusual cross-section of the Megaliner fuselage and the two cabin floors. The cross-section of a Megaliner like the A3XX fuselage is not circular, as is ideal and standard for a pressure vessel like a fuselage. Details of the new design had to be tested first in full-scale tests before Glare was ready to be applied in this type of aircraft. The GTO was not part of A3XX development for Airbus, but was meant to perform basic research to make Glare finally ready for application in different types of aircraft.

In July 1997 the GTO project to establish technology readiness of the material was started, controlled by Structural Laminates and subsidised by NIVR, while Structural Laminates, NLR and Delft University would carry out the required sub-projects. About one hundred sub-projects were divided into seven working groups:

1. Material and qualification, to determine material properties and carry out qualification of the material.
2. Methods, to generate and verify analytical methods to predict the mechanical properties of Glare structures.
3. Design concepts, to define concepts of how a Glare structure should look.
4. Manufacturing, to study manufacturing of Glare products on an industrial scale.
5. Specialities, for special properties such as burn-though resistance.

6. Spin-off, which was required by the Dutch government to generate the application of Glare in secondary aircraft structures and in other applications, outside the aviation industry.
7. Maintenance, to study possible damage, inspection and repair methods.

Airbus had appointed Fokker to be responsible for the qualification programme, but just as Airbus, Fokker and SLC were agreeing on its content, Fokker went bankrupt. This created an enormous delay for Glare, and qualification of the material did not start at GTO until April 1999. Soon the various working groups came together to specify the different sub-projects. The starting point was usually the hard-won experience of Delft, especially the findings given in the PhD-reports and the many projects recently carried out by the A3XX-students. Unfortunately, it appeared to be difficult to get input from the German side and this was necessary for the acceptance of the results afterwards. The basis of acceptance within the company was still too small and this remained so for a long period of the project. However, this weakness in organisation was counterbalanced by individuals within the organisation, like Thomas Beumler and others, who kept various sub-projects running although the formal organisation chart did not always include them. In this case, support did not come from the top but had to be achieved from the bottom up. As Hinrichsen put it: "We live in an imperfect world, and this is only possible with inventive people." The communication between Hamburg and the GTO co-ordinators necessary to harmonise plans with the Airbus consortium's wishes was mainly achieved via meetings in Delft and Hamburg. Finally, in 1998, EADS became seriously involved and this accelerated the work considerably.

For example, on the 21st and 22nd of January 1999, a big meeting took place in Hamburg to present results and discuss future plans. In this way, the GTO work could be integrated into a bigger plan called the Glare Technology Plan. This latter plan also incorporated work done by EADS and Fokker, focusing mainly on such things as design aspects, cost studies and industrial concepts. Such meetings usually produced many new questions that were added to the already long list: "Should the edges of Glare be protected?"; "What happens when a Glare fuselage is exposed to the hot exhaust gasses of the APU of another aircraft?"; "How to find corrosion in the hidden layers of Glare?"; "What are the in-service experiences with the material?"; "How can repairs be made?"; and so on and so forth.

Paul Kuijpers with a Glare panel being exposed to hot exhaust gasses of an APU of a Boeing 747.

Planning

Just as the Glare project was picking up speed, the co-operation between AKZO and ALCOA came to an end. It was also decided to wind up the activities of SLC. Fortunately, Daan Krook managed to get a production license for Europe for AKZO, and by doing so Structural Laminates Industries (SLI) could be saved. Gunnink's staff of Structural Laminates-bv was transferred to SLI. Also the concentration in Europe achieved by separating SLI from SLC turned out to be politically advantageous in the light of the heavy competition between Airbus and Boeing. However, it was AKZO's policy to go back to its core business and so it put SLI up for sale. At that time the interest within Airbus was still too small for it to be interested in buying SLI. After long negotiations, and with the support of the government, SLI was bought in December 1998 by Stork and subsequently became a daughter company of Fokker Aerostructures. However, these events meant that the material technology was now part of an aircraft component manufacturer, which limited the possibility of widespread acceptance of the material. On the other hand, Airbus liked the idea that the production of Glare structures was now in the hands of an experienced supplier, although the matter of the patent rights was still a big issue as it made Airbus dependent on Fokker Aerostructures. Fokker Aerostructures had inherited the reputation of the old Fokker, which had made metal bonding an accepted technology in aviation, and this helped to create trust in its manufacturing capabilities for Glare. Here too, a Delft connection existed: the president of Fokker Aerostructures, Kees de Koning, graduated from Delft where he worked on the formability of Arall in the early 1980s and played a significant role in the discussions with the Germans on the industrialisation and commercial aspects.

Both EADS and Fokker Aerostructures were very busy with different projects and, lacked the manpower to set priorities, and therefore they did not fully support Glare from the start. At first, Fokker Aerostructures did not expect to have much of a business case with Glare. The material did not fit their business strategy, which was aimed at the integration of systems, such as the design and manufacture of aircraft flaps. Fokker Aerostructures was targeting other work packages of the A3XX than Glare structures and Glare was thus not a high priority for the company. History showed these initial reservations to have been misplaced. In the end, only the Glare structures were successful, but as long as the application on the A3XX remained

uncertain their contribution remained limited. It was only after Hinrichsen reported in a paper delivered at the AAAF conference during the Le Bourget Air Show in 1999 that the cost of a Glare structure could be equal to an equivalent aluminium structure that Fokker Aerostructures became convinced of the viability of the material and gave the Glare development project its full support.

However, lack of industrial support was just one reason why it appeared to be very difficult to manage the GTO project. Senior manager Jeu Lambrichts of AKZO was hired to carry out the overall co-ordination of GTO, including SLI and NLR, while on the university side the co-ordination and planning was carried out by Ernst Schaaf, also of AKZO, from early in 1998. Jeu Lambrichts took over the position of Cees van Hengel who energetically led GTO in the difficult early days of the project when all the project proposals were still blank sheets of paper. Students like Alexander de Haan assisted by putting the planning of the GTO project in the computer. The university GTO group started in several rooms in the main building of the faculty, but was later moved to one big cosy open-plan office in the 'HLO-building' of the university. Both Lambrichts and Schaaf struggled with the informal type of organisation that was typical for the Delft culture. It soon transpired that Delft was also facing a culture shock, as it now had to carry out all required work within a specified time period – and within budget. Up to this point, the university had carried out some relatively minor projects with a budget in the order of 100,000 Dutch guilders (approximately 45,000 Euros), while now they were involved in 80 to 90 sub-projects with a total annual budget of several millions. Most of the GTO work was carried out in the university. TU Delft started the project at a moment when the money was still not guaranteed by the government, hiring former students and taking considerable financial risks. Moreover, the work had to be carried out, and the results delivered, according to a fixed time schedule parallel to the development of the A3XX. Planning was constantly under discussion, but accurate input was not always available.

For example, Glare material never arrived on time. The numerous specimens always took more time to produce than anticipated and priorities at the testing machine were hard to predict. Besides, the very nature of testing meant that one could never know what would happen during the work. Sometimes more tests had to be done than had been foreseen in order to explain unexpected results. The output of one project was often input for another and therefore the problems in sticking to the schedule listed

on the planning board accumulated. Planning deadlines were continuously shifted, but as Lambrichts liked to say, “the alternative to an inaccurate plan is a gut feeling”, meaning that without a plan, one never has a real sense of the required capacity in terms of manpower and machine hours. For the university staff, even the idea of planning was hard to deal with, and schedules were made only with reluctance. Project planning was also difficult because of the many aspects and partners involved, and also because student projects continued to be conducted in the lab and these had to be kept going in the midst of the vast amount of GTO work. A continuous problem was setting the priorities of all the projects: in meetings, all sub-projects usually received priority number 1, which created a situation that was obviously impossible.

Having to work according to the quality standards required in this type of project was also new. Material and specimens that went through the lab had to be documented carefully and labelled and stored after testing. In the past, most of the work had been carried out by students. In GTO students were also involved, but the quality control had to be much stricter. For example, it had to be absolutely certain that the right load was put on the specimen during a fatigue test. Such work is not typical for a university and Delft’s baby was delivered only after what seemed to everyone concerned to be a very hard labour. Scientific work and long-term work aiming at new technologies were now partly replaced by the production of raw data. However, it was not standard work. A lot of new aspects of the material came to light and fundamental research had to be undertaken to find solutions.

For the university, staff and students alike it was an important learning experience to be involved in this way in realistic material and aircraft development for a big company like Airbus. Another new feature was the fact that being involved in such a large aircraft development programme required the inherent confidentiality of information.

Airbus’ nightmare scenario was that its precious new knowledge would fall into the hands of Boeing. In the light of the open nature of a university environment, this was not an easy issue. It also stirred ethical questions about academic freedom and about the responsibility of the university to gather open information for the benefit of society. Theoretically the issues of planning, quality, and confidentiality could never be resolved. However, in practice there were few serious problems. Another bottleneck was that the small SLI staff of four or five people had to technically supervise the proposals for work of up to one hundred sub-projects, assess the results

and deal with any problems, and in the meantime keep in contact with Airbus and its partners. A mission impossible since, for example, Roebroeks had to rush off at least once a month to give a presentation somewhere within the organisation of Airbus and its partners to save Glare from yet another 'near-death experience'. Inevitably, proposals and draft reports spent too much time on desks after a lot of hurry and stress to produce them. SLI's supervisory role in these stressful times created some distance between the university GTO group and the SLI staff, even though they had worked well together for years by this time. The GTO project officially wound up at the end of 1999, but a new plan was written for the period 2000+ and the project continues under the name GRP (Glare Research Programme).

People

The Delft University GTO group was headed by myself. For GRP this task was taken over by Jos Sinke. As time went on, more Delft people became involved, including Tom van Baten, Jens de Kanter, Kees Paalvast, Frans Oostrum and Serge van Meer. In the current chapter more names have to be mentioned because the group of people involved now expanded rapidly. Many of the GTO staff were former students: Pieter Boersma, Peter Hooijmeijer, Michiel Hagenbeek, Occo Jan Bosker, Bob Borgonje, René Alderliesten, Peter Broest, Maurits IJpma, Fred Pellenkoft, Krishnan Gonesh and last but not least Paul Kuijpers, who played a very important role. Former Fokker employees who left after the bankruptcy were also hired: Johannes Homan, Professor Piet van der Schee and Niels Jalving. For the final work on Glare, PhD-students were needed to get all hands on deck: Thomas Wittenberg, Remco Coenen, Tjerk de Vries, Eelco Jansen, Reinier de Rijck, Tjarko de Jong, Arnold van den Berg and Arjan Woerden. Tjerk de Vries played a key role as working group leader for the Methods group in Delft, since he combined managerial and technical skills in a balanced way. De Vries communicated a lot with Van Wimersma to establish the connection between the Large Aircraft Division and Delft. Due to the amount of test work, we also had to break with the lab culture wherein every staff member carries out his own test work. Technicians were hired from the company RepAir to produce material and specimens and also to do test work.

A very important part of this final stage before industrial application was quality control. PhD-student Remco Coenen did work on inspection

techniques for Glare quality control. He used ultrasonic inspection (C-scan) methods to check the laminates for porosities and delamination after fabrication. He paved the way for a cost-effective quality control system, which is very important for the production of the material. The GTO work slowed down the PhD-studies, but it also added a lot of value to the various research projects and resulted in very mature and experienced PhDs. Despite stress and the changes in culture, the university group remained a group of friends. The trip that the whole group took to the area around Arnhem for a visit to one of the AKZO plants, followed by a golf clinic and an excellent dinner in the evening, is still remembered.

Delft now had a considerable task force. It had found its place as a research institute in the Dutch aviation sector for which it had fought so long. Recognition also found its way to the university, as it received all due credit from Airbus, not only as the place where Glare had been developed, but also as a centre of competence. The co-operation was excellent. Next to the drive and enthusiasm of the young people from Delft, the rich experience of NLR scientists like Wim van der Hoeven, Walter ‘t Hart, Arij de Koning, Lambert Schra, Joost van Rijn, André de Boer and Jaap Heida played essential roles in guiding the working groups and communicating with specialists in Hamburg, something that was difficult for the youngsters from Delft. The difference in culture between Delft and the NLR remained, but now the two research institutions became more complementary. NLR was also very busy on other projects such as the Joint Strike Fighter, one of the proposed aircraft projects to replace the F-16. It therefore had only a limited test capacity available for GTO, and a lot of the work had to be done in Delft.

At the same time, the co-operation with Fokker Aerostructures moved to a new level. After the bankruptcy of Fokker, the company had to find its own place as a designer and builder of aircraft components as a relatively small player in a business with high risks and small margins. Located in the Netherlands, it also faced a relatively high level of costs. Being small, the company was very vulnerable because each discipline could only be covered by a small number of people. Research like GTO could never receive the priority it had in Delft and therefore old tensions sometimes revived. However, SLI, Fokker Aerostructures, NLR and Delft had to close ranks in this new situation to be able to serve the customers: EADS, Aérospatiale and Airbus. Bad communications and changing roles had hampered relations in the past. Inevitably, problems remained in this project, which was under severe pressure to be on time for the A3XX. For example,

Joy at Fokker Aerostructures just after the decision to apply Glare on the A3XX; Gise Wit unrolls a banner with the text "Glare on the A3XX" from its main building in Papendrecht.

in the spring of 2000 Fokker Aerostructures decided to move its bonding plant from Ypenburg to Papendrecht for commercial reasons, but this caused a lot more problems with material delivery for a large part of the year. Such delays were difficult to accept within such a time-critical project as GTO.

Something happened in June 1999 that, because of my interest in ethics, I will not easily forget. We heard that the NLR had stopped specimen production because they had found that in similar circumstances carcinogenic strontium chromates from the primer are released in the air due to drilling and grinding of the surface. Because we were right in the middle of the process, and under great pressure to finish the work on time, any delay would have serious consequences for the chances of the application of Glare in the A3XX. On the other hand, strontium chromates are dangerous for the people in the workshop. We collected information and informed all concerned. They laughed, because they had already been working with the material for a long time. Besides, all kinds of other health and safety regulations that appeared ridiculous in their eyes had recently been forced upon them. The risk that working with Glare would produce the same circumstances as had been encountered by the NLR on bond primer were small, because the primer layer used in Glare was much thinner. After discussing the situation, some measurements were made to determine the composition of the air in the workshop during all kinds of processes: drilling, grinding, milling. Fortunately the chromate content appeared to be far below the acceptable safety level laid down in the regulations, but for the future other primers will have to be selected for Glare. In the short time frame of the A3XX development, it was not possible to make changes in the composition of Glare.

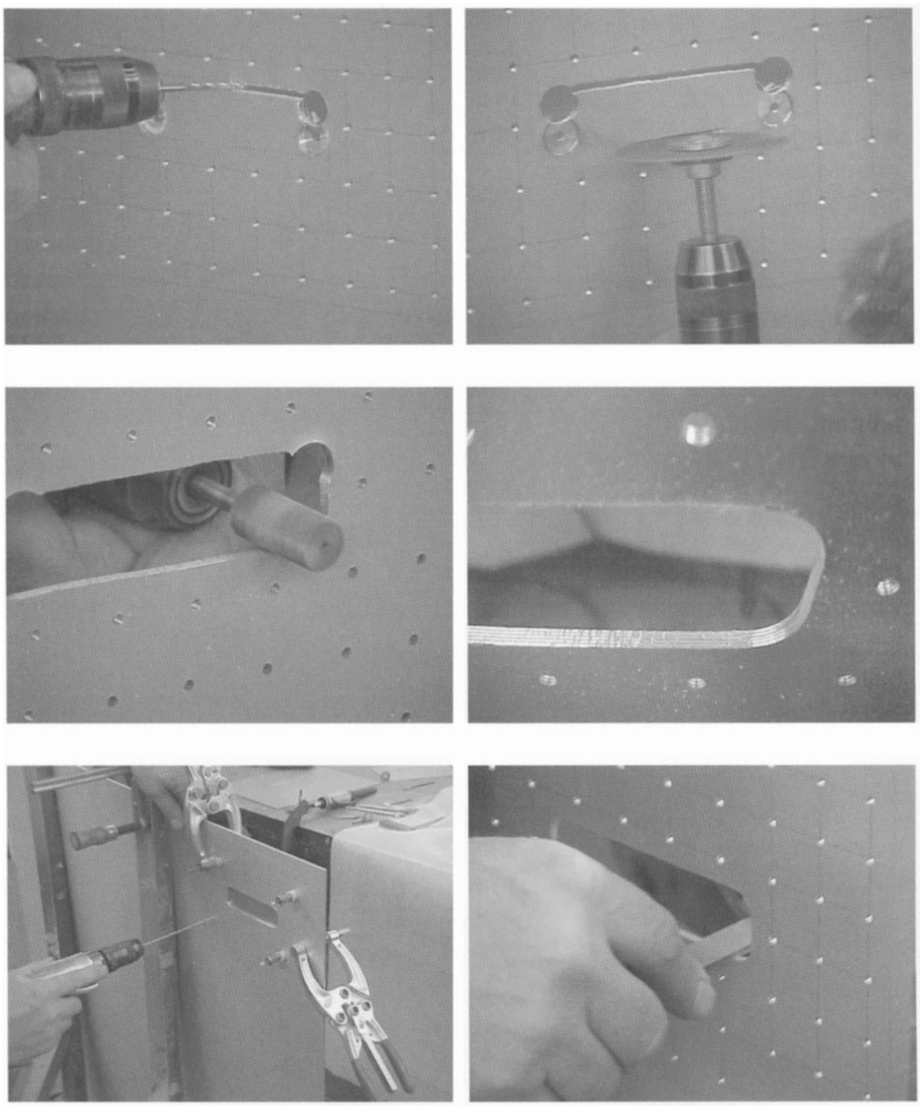
This was also true of other properties that appeared to be important during the GTO project. The aluminium alloy used to make Glare is currently 2024, the aluminium alloy already applied in the DC-3, which is very fatigue resistant. Because of the inherent fatigue resistance of Glare, it may be possible to change the alloy for a stronger variant with a higher yield stress, which may create a better balance of properties for the material. During the GTO project another improved Glare variant was developed. This has more glass fibre layers locally to increase the already high damage tolerance capabilities even further. It was not immediately pressed into service, however, since the risks would be too high and the time too short to solve any problems. This type of experience will lead to new variants in the future. Only when a material is actually in use on an aircraft can one start to gain

experience and optimise the concept. In actual practice, to wait for the perfect solution before applying a new material would mean we would still be building aircraft from wood. In that case, Hinrichsen could have been employed by Airbus even if he had remained a carpenter.

Airline workshop

An extremely crucial moment for Glare was an airline workshop that was hosted by Delft University on the 3rd and 4th of November 1998. This workshop was prepared by Airbus, where a lot of the work was done by Buwe van Wimersma of the Large Aircraft Division. In Delft, De Vries and Kuijpers acted as organisers. The whole Delft Glare group felt the significance of the event and worked extremely hard to deliver the required test results in time. At weekends, driving along the highway between Rotterdam and The Hague at night one could often see the lights in the lab burning where Kuijpers and Bosker were fighting against time.

The position of Buwe van Wimersma in the Large Aircraft Division was unique, since no other material suppliers but partners of Airbus were present in this division in Toulouse. His status there was not official, but he had the support of Hinrichsen and even wrote Airbus reports. Many people in the Large Aircraft Division opposed this, as this was in their eyes a strange situation, and therefore Jens Hinrichsen often introduced Van Wimersma in meetings simply as an Airbus employee, especially in the first meeting with the airlines. Aérospatiale was not happy with this situation and Van Wimersma was sometimes excluded from meetings. This opinion was shared by A3XX's Chief Engineer. For years he asked Van Wimersma when they met somewhere in a corridor in the building of the Large Aircraft Division: “Are you still here? We are not going to use Glare.” Early in 1997, Van Wimersma had represented Airbus in front of the airlines by explaining Glare to them for the first time. It was to Van Wimersma's credit that he had established good relationships with people in Aérospatiale, opening the door to this French company. He continually travelled back and forth between Toulouse and Delft to transfer data and questions. Together with Gise Wit, who arrived at the Large Aircraft Division as the Fokker Aerostructures representative a few weeks earlier, they fended off serious doubts on Glare whenever the going got tough. A couple of times, Glare came close to being thrown off the aircraft, but an open telephone line with the Netherlands and



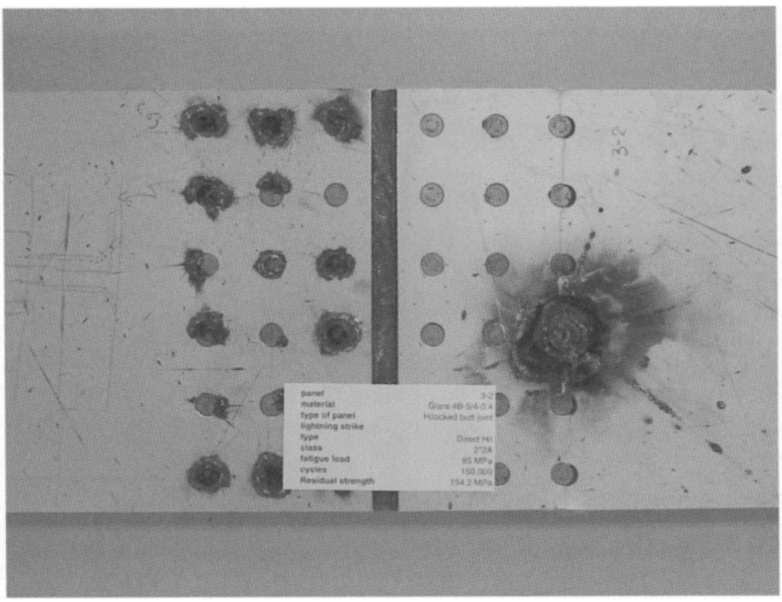
Repair demonstration shown at airline workshop.

some nights without sleep secured Glare's position again.

Presentations in the Delft workshop would be given by Van Wimersma, Hinrichsen, Eckart Wutke, Beumler, Gise Wit, De Vries, Jérôme Pora, Roebroeks and myself to a number of the key customers of Airbus, who participated in the development of the A3XX. The setting was one of the university lecture theatres. Eckart Wutke was a key person within EADS for production technologies. He strongly pushed the industrial aspects of Glare by looking after the plans of Fokker and the Glare production facility of EADS in Nordenham. Jérôme Pora had joined Hinrichsen's team from Aérospatiale, where he had worked on Glare and had become a promoter of the material. Thirty people attended the workshop and received information on design, fatigue, impact, lightning, corrosion, delamination and repair. For Glare, these two days were make or break and everybody realised this. It could be the end of two decades of development in Delft.

Fokker Aerostructures, SLI, NLR, Delft University and NIVR were all involved. This was unique, because normally Airbus only trusts its own representatives for these kinds of events, as wrong or badly presented information can have serious implications. Airlines are extremely conservative and actually do not want new material in their aircraft. The airline representatives attending the workshop were responsible for maintenance in their companies and represented Reality. Many critical questions were therefore fired at the speakers, especially to the poor presenters at the beginning of the workshop. Beumler and Van Wimersma managed to respond as a team to the sometimes aggressive questions. Roebroeks also played a fabulous role in the discussions. Boud Vogelesang came back from his holidays to be at this crucial workshop and helped create the necessary trust based on his overview and reputation. Yet criticism faded away as the workshop proceeded. The final blow was an 'on stage' repair demonstration carried out by maintenance personnel from Fokker Services in the lab, showing that Glare can be drilled and machined to repair it in the same way as normal aluminium. The airlines began to see that Glare was not being forced upon them but actually solved operational and maintenance problems because it is less vulnerable to impact, fatigue and corrosion damage. Demonstrations in the lab were essential to give the airlines a real feel for the material. It had to be shown that Glare was no longer simply an academic material, the toy of a university and of some enthusiastic specialists, but that it had been tested on a realistic scale. As a result of the workshop, the airlines made a list of action points of issues that

they felt still needed to be addressed and this list served as the basis for further developments in the common effort with the industrial partners. On the whole, the airlines were extremely pleased and therefore so was Airbus. After the workshop, Glare had reached the status of customer acceptance. The customers wanted the material and this was of utmost importance for Airbus. It could be used as an important argument in favour of the material.



Lightning strike damage in Glare panel.

Durability

Van Wimersma's main focus in the Large Aircraft Division was maintenance, since this was crucial for customer acceptance, but he also paid a lot of attention to durability, a highly controversial subject for a new material. Since Aérospatiale in Toulouse treated Glare based on their composites background and the Germans in Hamburg from a bonded metal structure culture, test procedures and specimens used to verify the long-term behaviour of the material were very different. The Germans had bonding experience because they already introduced bonded structures in Airbus' first aircraft, the A300, while the French were more oriented towards composites. The durability work was initiated at the end of 1998 and had to

be completed by September 1999 to be in time for an important decision with respect to application on the A3XX in October 1999. One of the key remaining issues was the maximum operating temperature of the material. When an aircraft is on the ground, the surface skin of the aircraft can become very hot, but in this situation the material carries hardly any load. This high temperature is therefore not realistic for a test. When the aircraft takes off from the runway and the structure is loaded the temperature is reduced, but by how much?

It took a long time before test procedures were fixed, but after that the project was carried out on schedule. The first discussions on the test results took place in August 1999. The results were dreaded since large strength reductions could be present in Glare which could very well lead to knock-down factors on strength which could, in turn, let the weight reduction vanish. A big relief was felt when the overall strength reduction was found to be limited to 15 percent. A large number of different tests were carried out from which it was learned that the most critical items for Glare in the design appeared to have low strength-reduction factors. It was not an easy task to interpret and communicate the test results. Of course the reduction had to be taken into account as a knockdown factor on the design values for Glare. Nonetheless, the final outcome of the testing showed that significant weight reductions of the order of 1200 kg were still possible for the A3XX.

During the GTO project, discussions with the Airworthiness Authorities started and the European Joint Aviation Authority (JAA) was informed about the features of the new material. Representatives raised many questions that had to be addressed and which will serve as part of the certification process of the A380.

In April 1999, the first experimental installation of a Glare fuselage panel was achieved on a German *Luftwaffe* A310. This was again carried out by Beumler, who had been looking for an opportunity to get a flying demonstrator aircraft for months. The lack of practical in-service experience remained an important item in any discussion and this had to be circumvented. The problem was to identify an appropriate aircraft since the material was still unqualified. For competitive reasons it was not possible to install Glare on an aircraft that might enter the United States, since the American authorities would have to be informed in that case. The German Air Force seemed to be the right candidate, although this necessitated civil *and* military certification. Beumler was able to ‘infect’ Mr. Horstman from EADS, who has close connections to all military organisations, with the

'Glare virus' and together they managed to get permission to install a panel in an A310 of the *Luftwaffe.* Heidenwolf managed contracts with Airbus Industrie and Lufthansa Technic, who installed the panel. Fokker Aerostructures did the design together with EADS experts and provided the panel. EADS did the strength justification and managed the certification. Once the aircraft had been identified, the panel was operational within nine months.

The panel provided useful production experience that proved that a different splice design was necessary, because the initial design resulted in a badly produced first panel. The installation of the A310 panel was also the group's first experience with the extensive documentation needed to assure product quality.

Glare demonstrator panel on an A310 of the German Luftwaffe.

First riveted Glare repair.

The qualification and certification of the *Luftwaffe* panel would lead to a second Glare application on an A310 aircraft. A year later, the Hamburg team found that a Fedex aircraft, located at *Elbe Flugzeugwerke* in Dresden for conversion from passenger to freighter type, could be repaired with exactly the same material as that which had already been qualified for the *Luftwaffe* panel, and they took action. Within three weeks, some Glare had been found at the NLR, Fedex was talked into accepting a Glare repair, *Elbe Flugzeugwerke* had been convinced that they would like to carry out a repair using Glare, the EADS certification specialists had arranged for the necessary permission from the airworthiness authorities, and the repair patch had been milled to final size in the Nordenham plant and installed. Since then, a small primary-structure Glare part has been flying on an American civil aircraft.

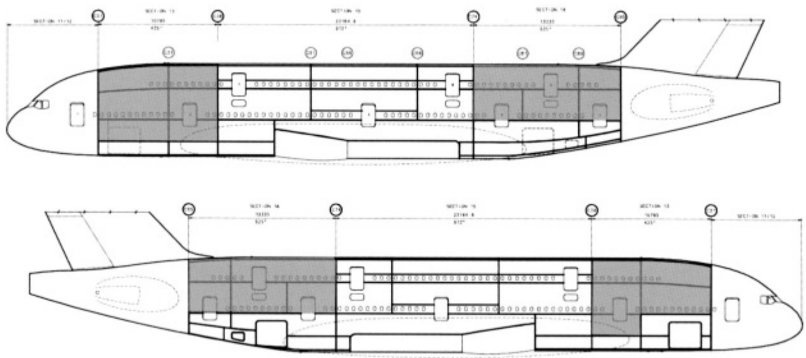
Selection for A3XX

Late in 1996, Airbus started its final materials selection for the A3XX, which was carried out in a very systematic way. A detailed risk assessment performed by Heidenwolf identified the risks associated with the application of Glare, by plotting a graph of the level of severity (the criticality) against the probability of occurrence. Elements that had to be taken into consideration were, amongst others: manufacturing costs, weight savings, design criteria, material properties and manufacturing processes. Associated risks that ended up in the top right-hand corner of the graph were unacceptable. All risks needed to be reduced to acceptable levels, in the green zone in the graph. An important factor in this selection process was that, as was shown in the first chapter, Glare fitted neatly into the history of metal bonding.

Airbus had already used metal bonding in the past on its first A300 aircraft, and although they had encountered severe problems in the beginning because of corrosion along the bond line, better pretreatment had fixed the problem. In 20 years of service, no problems were encountered. The limited in-service experience of Arall and Glare was more of an issue: the Fokker F-27 tank cover made of Arall was the longest experience (>12 years), slightly longer than an Arall reinforcement of the Fokker 100 emergency door cut-out (>12 years), followed by the C-17 aft cargo door (>9 years), Rob Fredell's C-5A bonded Glare repairs (>5 years) and Soerjanto's Fokker F-28 cargo bay repair (>5 years). The decision to apply Glare on the

A3XX was taken in steps. Acceptance of the material was therefore also achieved in steps, and at every milestone there were sceptics who wanted to kill the material. Glare survived the feasibility phase that ran up to 1995 (material properties and potential applications), and also the concept phase of the A3XX running from 1997 to 1999 and ending in a Critical Design Review held on the 9th of November 1999. The review was successful for Glare, although serious problems had been encountered with Glare in Delft in March 1999: shear properties, residual strength, off-axis strength and blunt notch strength appeared to be relatively low. The application of Glare in the A380 appeared to lead to the type of problems that had not surfaced before in studies on Glare for smaller aircraft like the A330. There were times in Delft in which we lost our belief that the material would be successful. After the Critical Design Review, some risks were still too high in the graph and a risk mitigation phase was introduced to limit them. The design phase started including Glare in 2000, but it was never decided with absolute certainty that Glare would really be used. Nonetheless the outcome of deliberations was positive every time and thus the material stayed on the A3XX all the way to the end.

Artist's impression of Airbus A380.



Chosen Glare application area on A380.

In the summer of 2000, Jens Hinrichsen had to skip his holidays to study the implications of the first design computer calculations for the design in Glare. Dr. Schneider decided to reduce the risks further by reducing the area where Glare would be applied from the whole top section to two sections in front of and aft of the wing of the A380. This is still a very large area because of the sheer size of the A380, comparable to the complete area of the fuselage of an A320, and will lead to a weight reduction of 500 kg. Even so, some people still have reservations about the material. In July 2000, severe doubts were expressed within EADS concerning one of the properties of Glare that was reduced under higher temperatures. It was in the middle of the holiday season and several people, including Gunnink, had to rush back to Delft. It took a special meeting with Dr. Schneider and the EADS specialists in Delft to address these worries. Finally, the contracts on Glare between EADS and Fokker Aerostructures were signed in May 2001. This again created a lot of stress but this time especially for the Fokker employees, because the first Glare production panels must be delivered in September 2002. A new Glare production plant is currently under construction in Papendrecht.

Such construction activity indicated that the future for Glare remains positive. There is good cause to keep Glare on the A380, for the weight problems in the design have still not been completely solved at the time of writing. Even in 2001 there is a chance that more Glare will need to be applied. Perhaps further testing will lead to such a decision. Recently, material has been delivered for the full-scale fatigue test on a fuselage segment – the Megaliner barrel test – led in Hamburg by the former Delft PhD-student Tjerk de Vries.

Beginning

While most of the faculties in Delft are shrinking, the success of Glare, and of other projects, in combination with a clear philosophy led to a further growth of the Aerospace Faculty. In March 1999, the green light was given for a new building to be built for the staff and the institutes on material and production. In this building the Fibre Metal Laminates Centre of Competence (FMLC) will also be located. The FMLC is an independently operating foundation founded by Delft University, NLR and Fokker Aerostructures. It aims at further technological and business development for new applications and new variants of the fibre-metal laminates. The NIVR's new head, Ben Droste, played a vital role in realising this new institute. Jürgen Thomas and Jens Hinrichsen were prominently present at its opening on the 16th of May 2001, and both of them delivered speeches.

Part of the opening ceremony of the Fibre Metal Laminates Centre of Competence on the 16th of May 2001 with, from left to right, Vonnie Vogelesang (representing her husband), Van der Harst, Jürgen Thomas, Daan Krook, Jens Hinrichsen and Jan Willem Gunnink.

Hinrichsen stressed the importance of openness about this new technology to boost its further use. Companies that want to protect their knowledge will slow down new applications of the material, which will in the end be counterproductive. But Hinrichsen also had a sobering thought to offer his audience. He stressed that we have not yet passed the finish line with Glare, but are only halfway. The material has been applied, but the technology is still far from fully optimised and is not widely used. Even the advantages in terms of safety and reduced fuel burn still have to be proven in reality. This was just the first step in a new direction. It is, maybe, appropriate to quote Winston Churchill, who declared after the battle of El-Alamein: “This is not the end. It is not even the beginning of the end. But it is, perhaps, the end of the beginning.”

Epilogue

With this story I have tried to give an impression of the development of a new aircraft material in a university environment. It mainly highlights the roles and the intentions of the various actors, and I did not analyse in detail what type of knowledge was gathered in our lab or how exactly it was applied.

The type of knowledge that was obtained during the development can be loosely grouped into four categories: material data and behaviour, modelling, manufacturing aspects, and application and design oriented research (including work on the F-27, C-17, and A3XX). The first two types each had their own independent development by way of Master's thesis projects and dissertations, while the third and fourth types were strongly linked. Application oriented research, for example, for the F-27 wing panel and the A3XX, appeared to be essential to guide the first three types of basic investigations. Basic material development is impossible without an application in mind. For the first type (material data and behaviour) fatigue, damage tolerance, and durability were key issues and the results were

always compared with competing materials: aluminium alloys and composites. For the modelling work, the PhD-studies were essential since a Master's thesis does not usually allow enough time to cover a material property by fully modelling its behaviour (e.g. fatigue, buckling, impact, strength of joints). Two full-scale tests, i.e. the F-27 wing panel for Arall and the A330/340 fuselage section ('barrel') for Glare, were crucial to show that the results of the small-scale lab tests remained valid for realistic structures. However, the relationship between lab tests and real life remains problematic. Durability, for example, remained a difficult issue throughout the development, since it is impossible to simulate realistic aircraft use in a lab. In-service experience, no matter how limited it was, therefore played an important role in the argument for the application of Glare on the A3XX. Another ongoing problem was the economic aspect of the material. Per kilogram, Arall and Glare were seven to ten times more expensive than aluminium. Whether this was balanced by the reduced fuel burn and cheaper manufacturing of products could only recently be fully resolved, because investigation into these matters required the support of an aircraft industry and an aircraft to apply the material on. The use of splices to increase the maximum size of the material and going directly to the layup in a curved mould were both necessary to reduce the manufacturing cost level to that of aluminium, as required.

In hindsight it is striking that at the beginning of the development of Arall, the actors chose to manufacture semi-finished products, i.e. sheet material, and not products, especially because product orientation is customary for the use of bonding processes in aircraft industry. This applies to metallic as well as to composite structures. Delft's decision to involve material producers (AKZO, ALCOA and 3M) in the development, instead of the aircraft manufacturer Fokker, may have played a role in this choice. If so, the fact that this decision was taken shortly after Delft and Fokker had quarrelled was no coincidence. The step toward the manufacture of products in a curved mould, including splices and reinforcements, occurred relatively late in the development – in fact when it became apparent that the material cost of Glare sheets would remain prohibitively high for commercial application.

From the history of Arall and Glare, it became clear that the scientific process itself was not central to the success of the material, although the university in Delft was the pivotal point in the development. Instead of science, engineering inventiveness, overview and flexibility were vital.

The introduction of a new material affects many engineering disciplines: manufacturing, design, aeroelasticity, maintenance, damage tolerance, and so on. As Van Riessen[1] pointed out, the strength and weakness of modern technology is that products are split up and covered by many specialists by way of a separation of the different functions of the artefact. This makes it extremely difficult to introduce a new technology, because a large organisation like an aircraft manufacturer has to achieve interaction and the combined effort of many different specialists and departments. Delft 'beat' ALCOA's Technical Center in the contest of Arall versus Glare and convinced specialists in Airbus, not by scientific rigour but by inventiveness, engineering overview and flexibility. The development of Glare was driven by engineering as the interrelation of different material properties combined in a design. The strength of Delft engineers like Roebroeks, Vogelesang and Gunnink was their generalist's perspective on problems in contrast with the often narrow specialists' views in companies like ALCOA and Airbus.

As Van Lente and Mulder stated, *expectation* plays a key role for scientific and technological development.[2] A strong belief in the eventual possibilities of fibre-metal laminates like Arall, and later Glare, was crucial for the people concerned to continue the battle over the years, and also to overcome obstacles. The outcome was not certain until the very end of our story. The success of this new technology depended not so much on its intrinsic technical opportunities, as on belief and on the power of persuasion of the researchers and engineers that were involved. It was not the technology itself that laid down the direction of the development, but the continuous interaction between the researchers in Delft and their environment, their 'customers'.

Expectation plays such a significant role because, as Vincenti rightfully states, "growth of knowledge in engineering can be described in terms of the blind-variation and selective-retention model put forth by Donald Campbell."[3] Technological development takes place through variation s of

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[1] H. van Riessen, *Filosofie en techniek.* Kampen, 1949.

[2] H. van Lente and K. Mulder, 'The Dynamics of Expectations in Scientific and Technological Development', *Scientia Yugoslavica,* Vol. 15, (issue 3-4). The contents are also given in a Dutch report: Philip Vergragt, Karel Mulder, Arie Rip en Harro van Lente, 1990, *De matrijs van verwachtingen, ingevuld voor de polymeren Tenax en Twaron.* Den Haag: NOTA werkdocument no. 12.

[3] W.G. Vincenti, *What Engineers Know and Why They Know It - Analytical Studies from Aeronautical History.* The John Hopkins University Press, 1990, p.241.

existing technologies and these variations occur in a blind way. Blindness does not mean ‘random’ or ‘unconstrained’, but ‘beyond the limits of foresight or prescience’. The outcome of the variation cannot be foreseen and is still open and flexible. Fibre-metal laminates were first conceived as a variation of bonded metal structures. The optimised variant developed in Delft had extremely good fatigue properties, but at that moment the impact of the full spectrum of material properties on structural behaviour, manufacturing and the economy of the aircraft could not be judged and still had to be formed in response to the interaction with the various actors. Gradually a more complete picture emerged, but still hard proof was impossible to give. And although Glare has now been selected for the A380, the material still has to prove itself through detailed design work, manufacture and actual use. It also needs to improve in the way of real applications and experience. History shows that, as was also the case for aluminium, the accumulation of experience is vital to optimise the technology. That is why Hinrichsen considers that the development of Glare is, at this moment, only ‘halfway’. The fact that Arall and Glare were relatively small variations of the bonded structure has helped to diminish the perceived degree of blindness. However, for actors who started from the

Coffee table at the Structures and Materials Laboratory (around 1988).

Coffee table at the Structures and Materials Laboratory (2001).

perspective of working in composites, the variation was relatively large: glass fibre instead of 'normal' carbon and the introduction of metal, which was the competitor and predecessor of composites. For these actors, the step towards Glare was more difficult to take.

A prerequisite for success was a core group of people in Delft who shared their way of working: an approach of 'can do'. In this way it was possible to band together to fight off threats from the outside world: other institutes, or companies like Fokker and NLR, and even the university management. There were also threats from other Delft materials groups working on composites and on structures. It was important to find other 'believers' and champions to support the material and to adapt to circumstances. The laminate had to be kept alive by surfing on external developments: available sources of funding, new aircraft projects, interest of companies. The evidence of claims was shown in specimens, test data, reports and presentations. This was a risky and stressful business because wrong perceptions by outsiders could lead to the sudden death of the material at almost any moment. Actually the whole development was one

constant trial, since adversaries continuously tried to find weak spots in the material. Nonetheless, a shared vision regarding the possibilities of fibre-metal laminates remained firmly held in Delft, and we tried hard to enlarge our circle of believers and to strengthen the case for the material. The funding of the university provided a firm basis to keep the project running through the years. Further variations in fibre-metal laminates were included in response to outside influences, to make the material more suitable: the move from Arall to Glare, from wing to fuselage, from sheet material to structures, proved the importance of flexibility in adapting the initial ideas. The project went on from milestone to milestone: first a small application like the C-17 cargo door and the bonded repair of a C-5A, then the first large-scale tests in the shape of the F-27 wing panel and the A330/340 fuselage barrel in Hamburg, and finally the breakthrough in a large-scale application on the A380.

Delft avoided giving the impression that the technology would be completely new as much as possible. Qualification procedures, repair methods, analytical design tools and design concepts had to be as close as possible to the common practice for aluminium. A revolutionary product would not have survived the process, since the reduction of risk is so very important to gain acceptance. One had to adapt to the needs of the aircraft industry, and of the airlines. A ‘Kuhnian’ crisis, in which a completely new paradigm or concept was selected for an aircraft design, had to be avoided at all costs. In that respect, Glare’s position between composites and metals caused problems, as evidenced in the issue of durability.

As important as the technical struggle was the manoeuvring that went on in the political and strategic arena. The different approach, competition and sometimes even rivalry between the Germans and the French played a role. The German backing of Glare and the further development of know-how within Airbus was important. Earlier in the project, strategic decisions concerning the position of AKZO relative to ALCOA and the interests of the latter had profound effects. In some respects, it may be favourable to have to deal with different cultures and with competition, but the inherent tensions are not without risk. Politics also played a role in the fact that being the centre of the new material, Delft could assume a new role in the infrastructure of aviation institutions in the Netherlands as a research institute with a strong industrial focus, instead of playing only an educational and scientific role. It even changed Delft’s view of the education of

engineers, as became apparent in Vogelesang's inaugural lecture. This change continued to play a role at the background of the Glare development.

For the old Fokker company, the introduction of fibres in the bond lines leading to fibre-metal laminates represented a variation of bonded structures, while developments on combinations of metal and composites in the U.S. and in the U.K. came from a different approach. With the positive experience of Schijve and Vogelesang in the field of fatigue of laminated structures, the development in Delft soon focused on the optimisation of the laminates' fatigue properties. Their ultimate goal was to solve the fatigue problem of aircraft. However, the fatigue problem was to a large extent already under control for aluminium and no functional failure of the existing technology was apparent. Fatigue was no longer the overriding issue it had been just after the Comet crashes. The industry was not asking for the solution they were offering. Later, new findings proved that Glare has favourable characteristics other than fatigue resistance: burn-through, impact, explosion resistance, and cost reduction by part integration. These were added to the story in the 'object world' of Glare. For a long period it actually appeared as if Glare had no negative properties at all, until it was found that moisture lowered the strength of the material and high temperatures reduced adhesion.

Vincenti's notion of 'blind variation' leading to an unknown future is in line with the study performed by Eric Schatzberg[1], who tried to interpret the change from wooden to aluminium aircraft structures in the 1930s using the power of symbols and ideology as important initial drivers behind this development. Material choice is not a pure, rational, straightforward technological and economical optimisation. It is largely a matter of design that cannot be fully schematised. If a variation is blind, than something other than rationality must be the driver. According to Schatzberg this is ideology or belief. In the common understanding and culture of engineers, not only material properties but also the symbolism of material has a place in determining the direction of technological development. Wood symbolised the traditional technology of craftsmanship, whereas metal was considered the material of the future and of the modern, industrial era. Aluminium represented, according to Schatzberg, technological progress and the power of scientific predictability. Therefore the wooden aircraft became obsolete before the advantages of aluminium were proven, and even while wood was

[1] Eric Schatzberg, *Wings of wood, wings of metal - Culture and technical Choice in American Airplane Materials 1914-1945.* Princeton University Press, 1999.

still actually superior for aircraft construction. This does not mean that today's aircraft could still be made out of wood, but that the technological and also the economical advantages were not yet clear at the moment that a direction was chosen at that particular crossroads of technological development. Of course engineers, entrepreneurs, financiers and bookkeepers do their calculations during that new phase of development as Dierikx[1] rightfully claims. However, the margins of uncertainties are larger than the accuracy of those calculations. The outcome of calculations depends heavily on what is put in and the result is judged on what is believed to be true. A fierce debate took place between engineers on the pros and cons of wood and metal, similar to the story of Glare. Promoters of metal frequently used the symbolism of aluminium by attaching metal to progress, modernity and science, while wood was associated with backwardness, traditionalism and craftsmanship. This resulted, according to Schatzberg, in a shift that brought work on wood technology to a standstill while all efforts were invested in the further development of metal. In Schatzberg's view, a community of aviation engineers has a set of common beliefs and the power of this mindset is very strong and hard to break. He even speaks about 'mythology' (p.5). It is indeed true that technical choice is indefinite. Like artefacts represent a cultural meaning, materials also have specific connotations. For example, wooden artefacts, like toys, are associated with the 'natural', while plastics are considered artificial. Such ideas play a role in the material selection process. The historian Lewis Mumford[2] even made a division of historical periods according to the materials used. Mumford also found that metal was associated with progress.

The indefiniteness of technical choice is a central notion of the idea of the social construction of technology *as* developed by Bijker[3] against the idea that technology is developing according to fixed paths, determined by efficiency, which would lead to an autonomous technical development. Technology is the result of choices made by human beings. There is not one most efficient way that can be calculated beforehand. The road that is taken is chosen on the basis of what is expected and this influences the future.

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[1] M. Dierikx, 'Wings of Silver, Wings of Gold', in: A. Vlot and C.J.A.R. Vermeeren, *Around Glare - the context of a new aircraft material.* Dordrecht: Kluwer, 2001.

[2] L. Mumford, *Technics and Civilization.* Harcourt Brace & Co, 1934.

[3] W.E. Bijker, *Of Bicycles, Bakelites, and Bulbs - Toward a Theory of Sociotechnical Change.* The MIT Press, 1995.

And as in every human choice, a mindset and system of symbolic meanings plays a role. Linked to power and conservatism this ideology can hamper development. Like Schatzberg, David Noble[1] has also indicated the importance of ideology for the shaping of technological change. The indefiniteness of technological choice in the arguments of Bijker, Schatzberg and Noble provides an opening for the influence of culture on the technical artefact and it implies that the choices are not neutral.

Schatzberg supports his view with the history of the change from wood to aluminium. After the First World War, the German manufacturers Junkers and Dornier proceeded with metallic passenger aircraft although they were not lighter and sometimes even heavier than the wooden equivalents. Two comparable aircraft at the time, the ‘metallic’ Junkers F13 and the ‘wooden’ Fokker F.II, both had a take off weight of 1900 kg and an empty weight of approximately 1200 kg. In 1920, enthusiasm for metal aircraft reached the U.S. The homogeneous material properties of metal and the great expectations played a key role, rather than the mere technical criteria. As a natural material, wood was discredited in the technical literature. On the other hand, the buckling behaviour of constructions in aluminium sheet material posed difficulties for the thin structures. The right structural concept for aluminium still had to emerge. America’s first metal bomber could only carry a hand grenade. Furthermore, metal structures were not bonded like wooden ones but joined by numerous rivets which was a very labour-intensive and expensive process. The first aluminium structures corroded rapidly and were no more durable than wood. It was clear that, beyond belief and expectation, vision and the passion for metal played an essential role to overcome all these difficulties. Initially, not only are new technologies not usually able to immediately solve bottlenecks – ‘reverse salients’ in the theory of Hughes[2] – but they may even start out by creating new ones. Personal belief in what is still not proven is necessary to overcome these obstacles. This was also true for the Glare development. The military played an essential role in propelling aluminium to success and for civil aircraft the vision of Henry Ford applied to the industrialisation of the aircraft industry was important.

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[1] D.F. Noble, *Forces of production: A Social History of Industrial Automation.* New York: Knopf, 1984 and *The Religion of Technology - The Divinity of Man and the Spirit of Invention.* New York: Knopf, 1998.
[2] T.P. Hughes, *Networks of Power: Electrification in Western Society 1880-1930.* 1983.

Any development, which takes place by gradually adding experience, will inevitably be very slow. This is what happened with Glare until the A3XX offered a window for application. A break-through is necessary to force a new technology into application. For the application of aluminium in the United States, this drive was created by the military. For them, a possible shortage of wood in times of war was an important argument. What is necessary is what Schatzberg calls a 'neue Stil', or a new paradigm. In engineering terms, this new paradigm killed further development of the wooden structures in which wood was combined with plastics. For Glare, the need for the most advanced technology for the A3XX created a break-through. What is evident in the story of Glare is that until the A3XX offered a window of opportunity, a gradual development took place, whereas the A3XX caused a rapid increase in technological readiness.

Whether a new technology gets this ultimate chance to prove itself capable of improving is to a large extent dependent on the faith of its adherents in its potential. Changes that are not in line with the common paradigm are hard to accomplish. The same fate as was first encountered by wood was later experienced by composite materials, according to Schatzberg. Plastics had negative associations. The application of the various metals and composites is therefore promoted by different camps within the aircraft industry. As was the case for aluminium, the support of the military was essential for the application of composites. Composites are still facing a hard task in attempting to break through the common metal paradigm for commercial aircraft, although on paper they can lead to very efficient structures. The same is true for cars, which can be much more efficient with present day technology, an opportunity that is blocked by the inherent inertia of the industry. The fact that Glare behaviour was close to that of aluminium made it easier than for composites to take the step.

This decision-making process for the application of a material in a certain product takes place to a large extent in what Bucciarelli[1] calls the 'object world' of engineers. This implies that the very complex issue of material selection is always reduced to more simple models and stories based on experience of the strengths and weaknesses of materials in various applications. It is within this world that the discussions between engineers regarding material selection take place. The significance of the airline workshop for the application of Glare on the A3XX (as explained in

[1] L.L. Bucciarelli, *Designing Engineers.* The MIT Press, 1994.

Chapter 5) can be explained by the fact that it profoundly changed the object world of the maintenance engineers of airlines, reprogramming it with presentations and demonstrations. It changed their perception of the material. Important for the object world is the relationship of the new technology to existing ones. Existing technologies serve as a familiar framework for reference, and for Glare this leads to comparisons with aluminium and composites. Glare had to find its position in the 'object world' between these two.

The descriptions of Vincenti, Schatzberg and Bucciarelli to a large extent hold true for the actual development of fibre-metal laminates. This material fitted the mindset of the metals specialists, because it was a variation of bonded metal structures. However, Glare did not fit in with the expectation of the composite specialists. Nonetheless, even to most of the metals oriented engineers Glare was a bridge too far. For a very long period in the development of the material, Glare was only supported by a small number of people. The development process was to a large extent a disseminating process, spreading confidence in the material by presenting evidence to everyone who could be persuaded to listen. The faith that is associated with blind variation is articulated in arguments that enter into the object worlds of engineers, where decisions are made. For the Glare development to be successful, the contents of the object world had to be filled continuously with evidence from research projects on Glare that provided arguments for its application.

For the Glare supporters the culture of Delft, with its friendship and informal organisation, proved to be essential. The informality of the coffee table and the inspiring leadership of Boud Vogelesang were crucial for students and the others involved, providing engineers from ALCOA, the US Air Force and Airbus to find a meeting place – and a home at times – in which battles had to be fought for Arall and Glare. This fighting spirit, in which advocates and adversaries crossed mental swords, was characteristic of the whole process. Delft provided a sally port.

It was certainly a battle. Even with hindsight, it is amazing how difficult it was for a material with such a high potential as Glare to get a chance. An important issue was the chicken-and-egg situation that exists in the aviation industry of no qualification of a material without application and vice versa. The same is true for the necessarily large investment needed to close the final gap with the application, finally achieved by the GTO project targeting the A3XX. The main obstacle for Arall and Glare appeared to be

GTO group at coffee table (2001).

the lack of consistency in company policies: ALCOA's move to diversification was followed by a retreat and a reorientation towards new aluminium alloys; Aérospatiale's difficulties with Glare; and Fokker Aerostructures' hesitation in adopting the material. This was compounded by the lack of really new aircraft designs, like the A3XX. By the end, during the A3XX project, Glare had gathered enough high-level management support to let initiatives from the engineers at the bottom of the organisation flourish. The support of Daan Krook, Jürgen Thomas and Jens Hinrichsen, and from officials of the Dutch government finally paved the way for Glare to be accepted for use in the A3XX. In the A3XX decision making process, it appears that once support is in place, belief in the material is strengthened by the same process that first blocked Glare, which now helps to overcome the obstacles. We used to have the feeling that we had to roll Glare all the way to the top of the hill, but once it had got over the crest and began to gain momentum, it was all the more difficult to stop. Even during the final phase, there were moments at which even those of us in Delft started to doubt whether Glare could really make it. But once success had ultimately been achieved, we suddenly found

that we had to get used to the idea that after the prolonged, agonising period of labour, Glare is no longer our baby. The influences on Glare's further development are so diverse, and so many, that the small circle of people who once sat down at the Delft coffee table together do not fully control Glare anymore. Glare is now on its own.

Appendix

This appendix gives the dissertations, Master's theses and preliminary theses of the students of the Delft Structures and Materials Laboratory, chair of Aerospace Materials. It comprises only the work on fibre-metal laminates.

A. Dissertations

1987

Verbruggen, M.L.C.E.	*Aramid Reinforced ALuminium Laminates: Arall. Adhesion problems and environmental effects.*

1988

Marissen, R.	*Fatigue crack growth in Arall, a hybrid aluminium-aramid composite material - crack growth mechanisms and quantitative predictions of crack growth rates.*

1991

Chen, D.	*Bulging of fatigue cracks in a pressurized aircraft fuselage.*
Roebroeks, G.	*Towards Glare - The development of a fatigue insensitive and damage tolerant aircraft material.*
Vlot, A.	*Low-velocity impact loading on fibre reinforced aluminium laminates (Arall) and other aircraft sheet materials.*

1994

Fredell, R.S.	*Damage tolerant repair techniques for pressurized aircraft fuselages.*

1995

Müller, R.P.G.	*An experimental and analytical investigation on the fatigue behaviour of fuselage riveted lap joints.*
Vermeeren, C.A.J.R.	*The residual strength of fibre-metal laminates.*
Verolme, K.	*The development of a design tool for fibre-metal laminate compression panels.*
Zaal, K.J.J.M.	*Residual strength analysis in aluminium alloy and fibre-metal laminates.*

1998

Coenen, R.A.M.	*Design of a quality assurance system for structural laminates.*
Hashagen, F.	*Numerical analysis of failure mechanisms in fibre-metal laminates.*
Tjahjono, S.	*Consequences and challenges of Glare for structural repair and newly designed fuselage structures.*

1999

Slagter, W.J.	*Static strength of riveted joints in fibre-metal laminates.*
Tempelman, E.	*Sustainable transport and advanced materials.*

2000

Vos, J. — *Characterisation of laminated construction materials based on ultrasonic reflection measurements.*

2001

Vries, T.J. de — *Blunt and sharp notch behaviour of Glare laminates.*

B. Master's theses

1980

Marissen, R. — *Onderzoek naar het vermoeiingsgedrag van gelamineerd plaatmateriaal met vezelversterkte lijmlagen.*

1981

Eikelboom, M.F. — *Theoretisch en experimenteel onderzoek naar het statisch gedrag van gekerfd en ongekerfd Arall plaatmateriaal.*

Heijdra, J. and Venselaar, K.

Het ontwerp van de vleugelonderhuid van de F-27 in Arall, een eerste opzet (Een Arall vleugelonderhuid voor de F-27).

Venselaar, K. — *Constructie-opzet van de Arall vleugelonderhuid voor de F-27.*

1982

Hengel, C.G. van — *Een eenvoudige methode voor de berekening van de statische eigenschappen van ongekerfd Arall.*

Swagemakers, E. — *Corrosievermoeiing van Arall.*

Warnar, F. — *1. De vermoeiingseigenschappen en de statische sterkte van symmetrische en asymmetrische HiLok stripnaden in Arall plaatmateriaal;*
2. De vermoeiingseigenschappen en de statische sterkte van geklonken lapnaden van 2024-T3 Alclad, 7075-T6 Clad en Arall plaatmateriaal;
3. De statische sterkte van Arall plaatmateriaal met ronde en elliptische gaten.

1983

Dames, R.A.C. — *Ontwerp, productie en vermoeiing van Arall beslaglippen.*

Pietersen, C.V. — *De produktie en het vervormen van Arall.*

Reumerman, R. — *Spanningsonderzoek naar het voorstrekken van Arall.*

Schijve, W.	*Onderzoek naar de konstruktieve uitvoering van de romp van de Airbus A-320 in Arall.*
Verbruggen, M.	*Determination of the moisture absorption of Arall.*

1984

Louwerse, G.M.	*Het "Blunt-Notch" en reststerkte gedrag van Arall.*
Schutrups, H.	*Het walsen en shot-speen vormen van Arall.*

1985

Bakkeren, D.J.	*The influence of the nickel coated T-300 fibre on the properties of carbon reinforced aluminium laminates.*
Kruijff, R. de	*Arall as crack stopper material.*
Pramono, A.	*Fatigue and residual strength tests on a monolithic aluminium alloy, a laminated aluminium alloy, and Arall.*
Stappenbelt, H.	*Onderzoek naar het effect van shotpeenen op de vermoeiingseigenschappen van 2Hx-2/y Arall.*
Verbeek, J.D.	*Arall: Chromic acid or phosphoric acid anodised? Effects on crack initiation, adhesion and durability.*
Verberne, C.J.	*The influence of the access door and the reinforcements around the access hole on the stress distribution in the Arall testpanel.*

1986

Geurts, W.G.H.	*De statische sterkten en (corrosie) vermoeiingseigenschappen van geklonken lapnaden met verzonken nagels, gemaakt van aluminium 2024-T3 clad, Arall 2H32 en Arall 2H42.*
Jolink, M.C.	*Ontwikkeling van de winded Arall tube.*
Mattheij, P.C.	*Constant amplitude fatigue tests on Arall 2024-T3.*
Vlot, A.	*Plasticity and formability aspects of Arall.*

1987

Haas, P. de	*Corrosion of Arall.*
Mangkoesoebroto, R.H.	*The effect of fibre volume fraction on the mechanical behaviour of Arall laminates.*
Racké, R.	*De economiche toepasbaarheid van Arall; Een oriënterende studie.*
Slits, P.J.J.M.	*Reststerkte van Arall met vermoeiingsscheuren (de invloed van variërende scheurlengten in de verschillende lagen van een laminaat op de reststerkte).*
Velt, J.C. in 't	*Fibre failure mechanism in Arall.*

Waleson, J.E.A.	*De acoustische eigenschappen van Arall-materiaal.*

1988

Bersee, H.E.N.	*Arall laminate tubes; Development, production, testing.*
Ekama, H.A.	*Analysis and modification of the Arall F-27 lower wing fatigue panel. Generation of a three-dimensional finite element model of the Arall F-27 lower wing fatigue panel.*
Haas, P. de	*Environmental fatigue of Arall laminates.*
Honselaar, C.H.	*Application of Arall in the A320 fuselage shell structure.*

Student Kees Honselaar and his specimens in front of the autoclave.

Mols, J.E.	*Thermal fatigue of Arall laminates.*
Oldersma, A.	*The impact of impact on Arall laminates and aluminium sheet materials.*
Rietdijk, B.	*A first approach to wing design in Arall laminate of the McDonnell Douglas C-17 transport aircraft.*
Slagter, W.J.	*Tapered Arall.*
Smet, B.J. de	*Onderzoek naar de consequenties van het vliegen met kleine scheuren in een Arall primaire vleugelconstructie.*
Smulders, E.H.M.	*Fibre fracture mechanism in Arall laminates with aramid fibres.*

Stapels, R.J.J.	*Low velocity impact on aircraft materials.*
Struik, P.	*Residual strength of Arall laminates, The fracture mechanics.*
Tooren, M.J.L. van	*Arall sandwiches en hun verbindingen.*
Velze, T.M. van	*Thermoplastics in Arall laminates.*
Vermeeren, C.A.J.R.	*The Arall blunt notch.*

1989

Erasmus, M.	*Design of a riveted Arall laminate lapjoint for the Airbus A320 fuselage.*
Gent, P.H. de	*Stretchforming of Arall laminates.*
Oost, R.C. van	*Structural design of an Arall laminate wing panel and associated joint at the wing root.*
Rodenburg, G.J.P.	*Invloeden van walsen en heet isostatisch persen op Arall; Dikteveranderingen in aluminium- en prepreglagen na walsen van Arall.*

1990

Kauffmann, N.M.J.	*Pillowing - Secondary bending in the pressurized fuselage skin structure.*
Kleinendorst, R.G.J.	*Corrosion properties of carbon Arall; Corrosion behaviour and mechanical properties of carbon aluminium laminates.*
Koos, M.G. de	*Peek carbon fibre reinforced titanium laminates: Adhesion and temperature influences.*
Kroon, S.J.	*The application of Glare in wing-fuselage front spar attachment fitting lugs; A feasibility study.*
Schoneveld, M.D.	*Arall, an investigation of material properties.*
Theunissen, C.H.A.M.	*Evaluation of a thermoplastic coating in the production of thermoplastic Arall.*

1991

Alberti, P.W.M.	*Formability aspects of curved Arall stringers.*
Bosma, H.	*Breukmechanica van delaminatie van Arall laminaten.*
Buijssen, F.J.M.	*Relation between the Fokker Bondtester readings and a varying bondline thickness in Arall laminates.*
Bulters, P.	*A comparison of low and high velocity impact; tests on several aircraft materials.*
Praag, R. van	*De vervormbaarheid van dunne sandwichpanelen met aluminium huidvelden en een thermoplastische kern.*

Syamaun, M.	*Bending fatigue of metal laminates (Arall and Glare).*
Teigen, R.	*Determination of off-properties of Glare; Blunt notch and fatigue behaviour.*
Tomter, R.	*Constant amplitude fatigue of Arall-2 and Glare-2.*
Verheij van Wijk, L.	*The technical and commercial feasibility of Arall floor struts.*
Verolme, J.L.	*Local buckling and crippling of Glare and aluminium; Design and test of hat stiffeners.*
Vroomen, J.T. de	*The linear elastic fracture mechanics of Glare; A method to predict the residual strength.*

1992

Breugel, E.A.J. van	*The manufacturing of complex double curved fibre-metal laminated components using preformed aluminium sheets.*
Caprice, M.d'A.	*Experimental evaluation of J-integral as fracture criterion for Glare laminates.*
Coenen, RAM.	*The ultrasonic inspection of Arall.*
Engelen, J.H. van	*The production aspects of fibre-metal laminate former frames.*
Holleman, E.	*The application of Glare in the Airbus A320 circumferential butt joint C47 -Detail design and full scale testing of butt joint panels-.*
Huijzer, E.L.	*Durability of Glare; The influence of water and temperature on the low-frequency fatigue behaviour of Glare.*
Kappel, E.A.	*Thermal- and deformation induced delamination of fibre-metal laminates.*
Maas, G.	*Modelling the springback of fibre-metal laminates.*
Mattousch, A.C.	*Structural application of stacked Glare - Design, production and testing of the CN-235 forward attachment fitting lug.*
Peters, W.P.C.	*Hybrid fibre-metal laminates; Application as fuselage skin material.*
Pho, J.C.C.	*Fracture mechanics of Glare and quantitative predictions of residual strength.*
Soetikno, T.P.	*Residual strength of the fatigued 3 rows riveted Glare-3 longitudinal joint.*

1993

Bröcking, R.G.J.	*Experimental techniques for R-curve determination from crack opening profiles in stiffened panels.*
Hakker, M.	*Bearing strength of Glare laminates: Test results and prediction methods.*

Ingen, J.W. van	*Static delamination of Arall-2, -3 and Glare-1; Influence of post stretching.*
Vanderstichele, H.	*Aluminium surface pretreatments for in-field bonded repairs.*
Velden, H.N. van der	*The buckling behaviour of Glare skin panels in the Airbus A300/A340 fuselage section.*
Verloop, S.B.	*The forming limit diagram of fibre-metal laminates.*
Vliet, A.C. van	*Reststerkte onderzoek aan Arall en Glare met part through cracks.*

1994

Bodegom, V.J.W. van	*Flight-simulation fatigue tests on blunt notched specimens of Arall and Glare.*
Borsboom, C.	*Damage tolerance of Glare lap joints in pressurized fuselage structures.*
Brouwers, G.L.A.M.G.	*C-scan software for ultrasonic inspection of fibre-metal laminates.*
Buters, M.C.M.	*From hole expansion to fatigue properties.*
Choi, A.Y.N.	*The residual strength of spliced fibre-metal laminates.*
Coesel, J.F.W.	*Drilling of fibre-metal laminates.*
Dam, J.J.D. van	*Undesirable curvature in lap joints due to rivet installation conditions.*
Tempelman, E.	*Recyclability and sustainability of fibre-metal laminates.*
Forno, E. Dal	*Experimental and analytical investigation on the initial buckling behaviour of fibre-metal laminates.*
Hoens, R.J.H.M.	*Bonded repair of Glare-3 fuselage skins: Mechanical properties and failure stress prediction.*
Deutekom, M.J.	*The effect of frequency, moisture and temperature on the constant amplitude fatigue behaviour of Glare-3.*
Medemblik, E.W.	*Titanium fibre-metal laminates.*
Mensink, J.L.M.	*Thermal properties and possibilities for space applications of fibre-metal laminates.*
Pangalila, I.A.	*Durability of Glare-3.*
Verseput, C.	*The production of seamless fibre-metal laminate tubes.*
Vingerhoeds, A.J.M.	*Optimization of the splice configuration: Environmental effects on delamination properties of Glare-3 material.*
Vos, R.F.	*Optimization of the splice configuration.*

Vries, T.J. de	*Various parameters concerning the residual strength of aircraft materials.*

1995

Bianchi, C.	*Impact on cargo floors - a comparison between different sandwich materials.*
Busch, H.	*Toward a digital imaging system to measure deformations.*
Dami, F.	*The use of Glare for the A3XX ultra high capacity aircraft wing box: a feasibility study.*
Dilodovico, G.L.	*Influences of metal layer properties on the residual strength of Glare.*
Duyne, R.E. van	*The effect of doublers on Glare riveted lap joints.*
Engelen, H. van	*Impact failure threshold energies of Glare-3, Carbon PEI and Dyneema-UD 66.*
Graafmans, G.M.H.	*Thermal behaviour of fibre-metal laminates; Thermal conductivity and the effect of thermal fatigue on Glare.*
Krull, M.	*The tensile properties and the impact behaviour of Glare-3 and aluminium 2024-T3.*
Michielsen, A.L.P.J.	*Finite element predictions for the residual strength of stiffened aluminium fibre-metal laminates structures.*
Pegels, C.S.	*A study on the residual stress of Glare-1.*
Schelling, J.A.	*A study on delamination and residual strength in Glare.*
Shaporifar, A.	*Crippling of fibre-metal laminate stringer-skin sections.*
Slagt, J.	*Small crack growth rates in a 2024-T3 sheet with a thickness of 0.3mm.*
Smit, J.E.	*Compression testing of stiffened aluminium and Glare.*
Smits, J.G.M.	*Impact induced delamination damage and residual compression strength of Glare-3.*
Suijkerbuijk, C.A.A.	*On strain rate effects during in-plane tensile testing and explosive forming of Glare.*
Tambunan, P.M.	*High velocity impact tests on ice protection plates of various aircraft sheet materials.*
Testi, S.	*A study on the compliance calibration for Glare.*

1996

Boertien, M.F.H.C.	*Strength of Glare after exposure to moisture.*
Brouwer, W.A.M.	*Evaluation of advanced materials for the wing of a next generation jetliner.*

Kuijpers, P.L.	*Increasing the residual strength of Glare-3 material.*
Langeveld, R.C.M.	*Development of ceramic and silicone based fibre-metal laminates.*
Mol, J.M.C.	*Post-forming properties of fibre-metal laminates (Glare).*
Oostrom, J.W. van	*Manufacturing double curved fibre-metal laminate shells.*
Panday, H.K.	*Application of Glare in the Airbus A320 fuselage section 13/14; A feasibility study.*
Plandsoen, Th.W.	*On Glare riveted joints typical for commuter aircraft like the Dornier Do-328.*
Siwpersad, D.R.C.	*Bonded Glare patches for the repair of cracked aluminium fuselages.*

1997

Droste, A.B.	*Sandwich floor panel design for the bulk cargo compartment of the Airbus A320 and A321.*
Ferdinandus	*Stress corrosion cracking susceptibility.*
Kevie, G. van der	*The modification of Glare to develop a more fire-resistant and non-delaminating fuselage skin for the Airbus A3XX.*
Kroon, E.	*Impact response of Glare-4; a candidate for the A3XX fuselage skin.*
Lynch, W.J.	*Effects of structural geometry on residual strength of stiffened Glare and aluminium panels.*
Moser, D.	*Glare faced bulk cargo flooring for Airbus Industrie.*
Nijssen, P.J.M.	*Qualititive investigation of disbond meachanisms under single-sided adhesively bonded repairs.*
Onna, M.B.S. van	*Design of the reinforcing skin area around a passenger door of an Ultra-High Capacity Aircraft.*
Verhoef, S.M.	*Design of a window belt area of an Ultra High Capacity Aircraft.*
Ypenburg, G.	*Analysis of stresses in the periphery of bonded Glare repair patches.*

1998

Boersma, P.J.	*Development of a fuselage panel selection tool for the Airbus A3XX.*
Bosker, O.J.	*Development of a Glare blunt notch strength prediction tool for the Airbus A3XX.*
Broest, P.	*Assembling 3D FML panels of undeformed aluminium sheets.*

Haan, A.R.C. de	*Effect of defects (A comparison between thick aluminium and Glare lap joints).*
Hausen, S.H.T.	*The development of fibre-metal laminates (1978-1998).*
Ruyter, W.A. de	*Residual strength investigation of Glare (Influence of multiple site damage and splices).*
Soede, J.	*General quality assessment of Glare.*
Verhoeven, S.	*In-service effects on crack growth under bonded composite repairs.*
Vervaet, M.	*Fatigue crack growth in thick Glare.*
Vissers, S.J.A.	*Detail design of a fuselage crown panel with a butt-joint for the A3XX.*
Woerden, H.J.M.	*Fuselage spectrum fatigue loading on fibre-metal laminates.*

1999

Alderliesten, R.C.	*Development of an empirical fatigue crack growth prediction model for the fibre-metal laminate Glare.*
Apsoro, Y.A.R.	*A preliminary research on the new fibre-metal laminate with M5 fibre.*
Broest, P.	*Assembling 3D-FML panels of undeformed aluminium sheets.*
Guichelaar, G.W.	*Preliminary design of a fancowl made of Glare.*
Hooijmeijer, P.A.	*Mechanical properties of spliced Glare panels.*
Massar, J.J.A.	*Crack growth predictions of bonded repairs by means of finite element models.*
Meesters, T.	*Trade-off study of the upper engine fairing of the Nimrod 2000.*
Mortier, W.	*Crack initation in Glare and aluminium patches for one-sided repairs.*
Ruyter, W.A. de	*Residual strength investigation of Glare.*
Sihombing, K.M.	*The application of M5-fibre in fibre-metal laminate.*
Venne, L.L.	*Investigation of a damage detection system for fibre reinforced laminates.*
Vesters, W.	*An investigation of stiffened panels.*
Voort, M.N. van der	*A new VA fatigue crack growth prediction program for bonded repairs.*

2000

Boer, T. de	*The development of an elevated temperature FML.*

Borgonje, B.	*The influence of elevated temperature on Glare after exposure to moisture.*
Brenninkmeijer, R.	*The effect of moisture ingress on the bonded repair effectiveness.*
Daverschot, D.R.	*Thermal residual stresses in bonded repairs; Analysis and experiments.*
Galen, R.M. van	*Effect of structure thickness on the performance of single-sided bonded repairs.*
Ginkel, A. van	*Optimization of Glare floor panels with respect to durability; part two: Inserts and edge closure design and testing.*
Heeringa, T.	*Finite element analysis of diagonal tension in stiffened Glare panels.*
Kieboom, O.T.	*Fatigue crack initiation and early crack growth in Glare at different temperatures.*
Kraker, L. de	*Increasing residual strength of Glare-3 skin panels by application of internal crack stoppers.*
Out, B.	*Tolerances of splices.*
Pellenkoft, F.	*Secondary bending in Glare.*
Reis, A.G.	*Titanium doublers in a Glare skin.*

2001

Brügemann, V.P.	*Fatigue allowable of the door surrounding structure of an ultra high capacity aircraft.*
Galen, R.M. van	*Effect of structure thickness on the performance of single-sided bonded repairs.*
Gonesh, K.A.M.	*Development of a fatigue crack growth model for surface cracks in Glare.*
Nawijn, M.	*Verification of a design method for the stability of stiffened panels loaded in shear.*
E.M. Wouterson	*F-16 fuel vent hole repair - Flight simulation loading and composite patch design.*

C. Preliminary theses

1982

Pietersen, C.V.	*Het buigen van Arall.*
Verbruggen, M.L.C.E.	*Duurzaamheid van Arall.*

1983

Bohemen, R.H.M. van — *Gewichtsvergelijking tussen een aluminium, een Arall en een CFRP vleugeldoos van gelijke afmeting.*

Louwerse, G.M. — *De optimale laminaat opbouw van Arall.*

Racké, R. and Hegemans, G.J — *Effecten van meerdere kerven op de statische treksterkte van Arall plaatmateriaal.*

1985

Geurts, W.G.H. — *Vermoeiing van Arall schalmen.*

Jolink, M.C. — *Nieuwe lijmen en vezels voor Arall.*

Verbeek, J.D. — *The meaning of anodic layers for crack initiation in Arall.*

Vlot, A. — *Het bewerken van Arall.*

1986

Honselaar, C. — *The residual internal stress distribution in Arall.*

Mattheij, P.C. — *Residual strength of Arall.*

Slits, P. — *Onderzoek naar een uitvoeringsvorm van de spant-huid-verbinding in een hoogbelaste romp bij uitvoering van de huid in Arall.*

Velt, J.C. in 't — *Vluchtsimulatie beproeving van een Arall boutverbinding.*

Waleson, J.E.A. — *De demping van Arall; Een orientatie.*

1987

Algovia, A.G. — *GRALL, The new "Arall".*

Honselaar, C. — *The residual internal stress distribution in Arall.*

Melman, J. — *Preliminary study on the compressive behaviour of delaminated Arall.*

Oldersma, A. — *Impacteigenschappen van Arall: Een orienterende studie over het gedrag van Arall, aluminium en composietmateriaal onder impactbelasting.*

Smet, B.J. de and Westenberg, R.B.M. — *Toepassing van Arall in een drukschot van een verkeersvliegtuig.*

1988

Hoften, G.C. van — *Patch repair of Arall laminate aircraft skin areas.*

Servent Miro, R. — *Preliminary study on the influence of three thermoplastic Arall fabrication process on the aluminium alloy sheets.*

Slagter, W.J.	*Application of Arall in stiffened wing skin panels for large heavy-loaded aircrafts.*
Struik, P.	*Residual strength of Arall; The thickness influence.*
Vermeeren, C.A.J.R.	*Het Blunt Notch gedrag van vezelversterkte aluminium laminaten bij variërend vezelvolume percentage.*

1989

Heijde, M.A.D. van der	*Tests for aircraft interior materials in fire accidents.*
Huitema, E.	*The influence of corrosion pits on the fatigue behaviour of Arall.*
Kleinendorst, R.G.J.	*Karakterisering en optimalisatie van het impregneren van glasvezels met poly-ether-imide.*
Langerak, N.A.J.	*Arall laminates tubes for pipelines.*

1990

Heur, J.J.M van	*De invloed van koppeling op het macro-mechanische gedrag van niet-symmetrische laminaten.*
Huitema, E.	*Cyclic condensation fatigue of Glare laminates.*
Scholte Albers, GAM.	*De delaminatie weerstand van Glare.*
Seegers, H.J.W.	*Thermal stress on aramid fibres in Arall.*
Tensen, O.J.	*The moisture absorption of Glare - Introduction; The weight gain curves, diffusion coefficients and calculated moisture profiles.*
Thuis, B.H.G.S.J.	*The influence of impact on the tensile strength and fatigue behaviour of Arall laminates.*
Tutucu, M.	*Minimum bend radii and springback angles of Glare-2 Laminates.*
Verheij van Wijk, L.	*The influence of moisture and temperature on the fatigue behaviour of Glare-4.*
Verolme, J.L.	*The compressive properties of Glare.*

1991

Alberti, P.W.M.	*The application of Arall in heavy loaded structures.*
Bosma, H.	*Gevolgen van lage snelheden impact op aramide Arall en Glare.*
Bulters, P.B.M.	*Static and ballistic impact tests on biaxial loaded cruciform shaped specimen.*
Coenen, R.A.M.	*Evaluation of ultrasonic indications in Arall.*
Hoileman, E.	*Glare as butt strap material for the butt joint at frame 467 in the Airbus A320 fuselage crown.*
Huijzer, E.L.	*Low-frequency fatigue of Glare-4; The influence of moisture and temperature.*

Kappel, E.A.	*Influence of internal stresses on selected material properties of fibre-metal laminates (Arall).*
Mattousch, A.C.	*Bearing strength tests on Glare sheets for the application in lugs.*
Mol, R.N.W.	*Fibre-metal laminates program codes available in the Structures and Materials Lab.*
Peters, W.P.C.	*Glare with various aluminium alloys. Applications in fuselage skin.*
Pho, J.C.C.	*Residual strength of Glare based on J-integral concept.*
Seegers, H.J.W.G.	*Thermal stresses on aramid fibres in Arall.*
Soetikno, T.P.	*Influence of a second bonding cycle on pretrained Glare-1.*
Syamaun, M.	*Bending fatigue of metal laminates (Arall and Glare).*
Verolme, J.L.	*Local buckling and crippling of Glare and aluminium.*
Vroomen, J. de	*Residual strength of Glare.*

1992

Boertien, M.F.H.C.	*Evaluation of solid S2 and R glass fibres vs. hollow S2 glass fibres for fibre-metal laminates.*
Brouwers, G.L.A.M.G.	*Upgrading the C-scan installation.*
Engelen, J.H. van	*Fibre-metal laminate former frames; A literature survey.*
Hakker, M.	*Geometry effects on the bearing strength of Glare laminates.*
Hordijk, C.	*Minimum bend radii and springback angles of fibre-metal laminates.*
Seegers, H.J.W.G.	*Thermal stresses on aramid fibres in Arall.*
Vanderstichele, H.	*Investigation of a low temperature curing structural adhesive for repair of cracked aluminium aircraft structures.*
Werkhoven, R.J.	*Testing of the rivet strength in Glare-3, Glare-4 and aluminium 2024-T3.*

1993

Boomen, P.P.M.	*The effect of elastic curvature and roll-forming on the fatigue life behaviour.*
Choi, A.Y.N.	*Residual strength prediction for fibre-metal laminates with splice: The crack growth resistance curve approach.*
Hartono, B.	*Lap joint shear testing of Glare-3, Glare-4 and aluminium 2024-T3.*
Hoens, R.J.H.M.	*Investigation of a room temperature storable epoxy film adhesive for bonded repair of aircraft structures.*

Medenblik, E.W.	*Candidate materials for elevated temperature fibre-metal laminates.*
Pegels, C.S.	*An investigation on constant internal stresses in post-stretched fibre-metal laminates.*
Vliet, A.C. van	*Literatuurstudie breukmechanica monolitisch materiaal en vezel-metaal laminaten.*

1994

Bröcking, R.G.J.	*Design study on the application of Glare-3 in an electronic access panel: Analysis of transverse loaded flat panels.*
Dam, J.J.D. van	*Detailed analysis for off-hole fatigue initiation.*
Deutekom, M.J.	*Environmental effects on the constant amplitude fatigue behaviour of aluminium, Arall and Glare: A literature survey.*
Duyne, R.E. van	*Doublers on a riveted Glare lapjoint.*
Hanssen, L.C.W.	*Onderzoek naar spliced laminates.*
Krull, M.	*Multiple fibre-layers in the lay-up configuration of Glare-3 laminates and the effect on impact behaviour.*
Suijkerbuijk, C.A.A.	*Strain rate behaviour of Glare-2 and -3 in longutudinal and longitudinal-transverse direction.*
Vos, R.F.	*Optimisation of the splice geometry.*
Vingerhoeds, A.J.M.	*Influence of fibre orientation and splice gap on strength.*

1995

Adriaansen, A.M.G.	*Post forming properties of fibre-metal laminates Glare.*
Engelen, H. van	*Elastic deformation traject in impact loading.*
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